A METHOD FOR COMPARING ALTERNATE PAVEMENT DESIGNS

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by

E.P. ULBRICHT

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

A METHOD FOR COMPARING ALTERNATE

PAVEMENT DESIGNS

To: G. A. Leonards, Director
Joint Highway Research Project

November 28, 1967

File No: 3-3-29

From: H. L. Michael, Associate Director
Joint Highway Research Project

Project No: C-36-54CC

Attached is a Final Report on the research project "Evaluation of Economic and Performance Considerations for Highway Pavements in Indiana" which was approved on May 10, 1966. The title of this report is "A Method for Comparing Alternate Pavement Designs." It has been authored by Mr. Edgar P. Ulbricht of our staff under the direction of Professor J. C. Oppenlander.

A method for objective comparison of alternate pavement designs with consideration of terminal serviceability, average serviceability and cost of the pavement is presented.

The report is presented to the Board for review and comment and for the record.

Respectfully submitted,

Harold L. Michael/jgp

Harold L. Michael
Associate Director

HLM:nf

Attachment

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Final Report

A METHOD FOR COMPARING ALTERNATE PAVEMENT DESIGNS

by

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ABSTRACT

Ulbricht, Edgar Pierron. M.S.C.E., Purdue University, August 1967. A Method for Comparing Alternate Pavement Designs. Major Professor: Dr. J. C. Oppenlander.

The purpose of this research was to develop a method for comparing a set of preselected pavement designs for a proposed section of state highway in Indiana. This comparison is based on consideration of both economic and performance requirements. The major portion of this study was devoted to obtaining a measure of the total performance of highway pavements with known design characteristics and traffic loadings.

The AASHO Performance Equations determined in 1961 at Ottawa, Illinois were used to predict the present serviceability trends with time of 160 study pavement sections. A serviceability trend is a measure of the performance of a pavement. The AASHO equations were found to estimate the present serviceability of Indiana highways within acceptable limits of precision.

However, additional precision was obtained by modifying these equations to reflect the lower initial serviceability levels of Indiana rigid, flexible, and overlay pavements compared to the AASHO Road Test pavements. The modification was accomplished by regression analyses between the predicted

and measured present serviceabilities of the study sections. The regression equations have been termed the Indiana rigid, flexible, and overlay serviceability equations.

From the Indiana equations, tables were compiled listing the anticipated performance of various pavement designs under a wide range of traffic loadings. The tables included in this report permit determining the performance-to-cost ratio of each of the pavement designs to be compared. This ratio can be used to select the proper pavement design for given traffic and environmental conditions.

When loadometer data are not available, the use of the AASHO and Indiana serviceability equations is facilitated by the technique developed in this study for approximating the number of equivalent 18-kip single axle load applications a pavement section has received. This estimate is made on the basis of the number of trucks traveling over the highway.

INTRODUCTION

The function of a highway pavement is to provide a roadway that adequately serves the demands of the road user with an acceptable level of performance. The purpose of pavement design is to select a structural system for the supporting way which usually includes a compacted subgrade, subbase, base, and surface. This supporting way must fulfill the needs of the anticipated traffic in an acceptable manner over the service life of the particular pavement. A properly designed, constructed, and maintained pavement is a major factor in providing economical, efficient, safe, convenient, and comfortable highway travel.

Most newly constructed pavements satisfy the expectations of the highway users. Because a pavement is subjected to traffic and the elements, the surface shows increasing deterioration and deformation even if the pavement is designed, built, and maintained to high standards. As cracks, bumps, and ruts develop, the riding qualities of the pavement become less acceptable to the road users.

Although the methods of pavement design in use today do consider traffic loads and climatic conditions, no attempt has been made to evaluate the accumulative effect of traffic

in ascertaining the proper pavement thickness. Recent research has shown the importance of considering the number of axle applications a pavement has received and the resulting effect on the ability of the pavement to serve the traffic.

Most design procedures implicitly assume that the pavement lasts indefinitely in its original condition if certain requirements are fulfilled. In the case of theoretical and semi-theoretical methods, such as the Kansas Triaxial Method and the Portland Cement Association Design Procedure, the stresses and/or strains are not permitted to exceed certain predetermined maximum levels. For empirical procedures, such as the California Bearing Ratio Method and the Group Index Procedure, a certain minimum thickness for each component layer is the requirement for pavement longevity. The required thickness for each layer depends upon the results of certain arbitrary tests.

A few methods do permit consideration of the effects of traffic volumes (and indirectly, different axle load distributions) on the design life of the pavement, but this allowance is included only by adding an empirical modification to the basic design procedure. These modifications implicitly acknowledge the final structural failure of the pavement due to the combined effects of traffic and climate, but no design procedure takes into account the gradual deterioration of the pavement prior to failure.

In an effort to advance the field of pavement design,

the significant relationships between the changing surface condition of pavements of different structural designs and the weight and number of vehicle axle applications which each pavement receives were determined during the AASHO Road Test. This test was sponsored by the American Association of State Highway Officials, the Highway Research Board, and other organizations.

The relationships determined at the Road Test form the basis of the AASHO Interim Design Guides, which utilize the most up-to-date design concepts. (1,2)* These design guides are already being used by the Indiana State Highway Commission in conjunction with other design procedures. (6) However, even the AASHO procedures consider just the condition of the pavement surface when it requires replacement, and not the changing condition of the pavement throughout its expected life.

In contrast to other design procedures including the AASHO guides, this study incorporates a measure of the performance of a pavement throughout its anticipated life into a procedure for selecting the most economical pavement design for a given highway section. The tools used to determine the performance capabilities of proposed designs are the serviceability relationships developed from the AASHO Road Test data. These relationships, commonly referred to as the AASHO Performance Equations, are semi-theoretical equations used to

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* Numbers in parentheses refer to articles in the List of References.

predict the ability of the pavement to furnish a safe transit to vehicles and cargoes, and a comfortable ride for passengers.

One of the purposes of this study was to develop a method of comparing alternate pavement designs for any given highway location in Indiana. This comparison is based upon consideration of both economic and performance requirements for rigid, flexible, and overlay pavement designs. An overlay pavement is a portland cement concrete pavement which is resurfaced with a bituminous mixture after traffic has deteriorated the original surface.

The derivation of this method required validation and modification of the AASHO performance equations to ascertain and reflect the differences between the soil conditions and construction practices in the State of Indiana and at the AASHO Road Test facilities near Ottawa, Illinois. Data for these modifications were obtained from a sample of 160 sections of pavement located throughout the State of Indiana. The sample was composed of 80 rigid, 56 flexible, and 24 overlay pavement sections. Slightly less than one-half of these sections were located in the Crawfordsville District of the Indiana State Highway Commission. The other sections were scattered throughout the remainder of the state highway system.

The use of the AASHO performance equations was further facilitated by certain simplifications. The most important of these aids is the weighted equivalence factor, WEF. The weighted equivalence factor is a single parameter which

completely characterizes the axle-load distribution of a traffic stream. The axle-load distributions used to calculate the WEF were obtained from 22 loadometer stations over a three-year period. An empirical relationship was determined by which the weighted equivalence factor is readily estimated from the number of trucks in the traffic stream.

The AASHO equations as modified in this study for Indiana highways have been termed the Indiana serviceability equations. From these equations an additional equation was derived to provide a single value representative of the performance of a pavement throughout its life. This equation is called the Indiana performance equation.

The Indiana performance equation was used to estimate the expected performances for various rigid, flexible, and overlay pavement designs. The effects on performance of various conditions of traffic volume, axle-load distribution, and design life were included in the tables and figures developed in this investigation. A suggested method for selecting the most economical pavement design for the level of performance required is presented. The need for further work in this regard is indicated.

A design procedure which includes a measure of the expected performance of the pavement under traffic permits:

1. Achieving the proper balance between performance and cost,

2. Determining the critical levels at which the pavement should be improved or replaced, and

3. Estimating the performance displayed by the pavement throughout its service life.

When pavement design is based upon the performance of the pavement, the general public profits because the optimal expenditure of the highway dollar is achieved. Further, such a design procedure benefits every highway user by providing smoother, more serviceable roads. This travel situation results in less fatigue for the driver, a more enjoyable trip for the passengers, reduced damage to cargoes, and lower vehicle operating costs. In general, a design procedure based upon the performance of the pavement allows the construction, maintenance, and operation of a balanced and optimal highway transportation system.

REVIEW OF LITERATURE

In recent years considerable attention has been devoted to the evaluation of the performance of different highway pavements for various loading and environmental conditions. The total demands to which a pavement section is subjected during its service life have been quantified in relation to the performance that is desired by the road users. These demand-performance relationships were developed from the study of traffic characteristics and pavement deterioration. From these empirical relationships it is possible to estimate the future pavement performance of a highway.

Several years ago it was not even possible to quantify the performance of a highway pavement in service, much less to predict the performance of a pavement prior to its construction. In this section, the current concept of pavement performance is reviewed. In addition, the units, methods, and precision to which performance is measured are discussed, as well as the equations which are used for predicting the performance of a highway pavement.

Pavement Serviceability-Performance Concept

In the past, the performance of a highway pavement was given only in terms of a general qualitative word description of the ability of the pavement to serve the traveling public. Although the description was vague and arbitrary, it attempted to answer the question of whether the pavement behaved in an acceptable manner before it had to be replaced.

Now the pavement serviceability-performance concept, which was developed by W. N. Carey, Jr. and P. E. Irick for use in the AASHO Road Test, permits a quantitative evaluation of the performance of a pavement. In this concept, performance is measured in terms of present serviceability, which was conceived by Carey and Irick as an estimate of the instantaneous performance of a pavement.

Definitions

W. N. Carey, Jr. and P. E. Irick, in the development of their concept of pavement performance, have defined present serviceability as "the ability of a specific section of pavement to serve high-speed, high-volume, mixed (truck and automobile) traffic in its existing condition." (7) In actuality, present serviceability is the average opinion of all highway users as to the quality of the ride experienced by the traffic passing over the particular pavement section. The present serviceability of a highway always pertains to the condition of the pavement at some specified instant in time.

Performance is defined in terms of serviceability, as a summary of the serviceability levels of the pavement over a period of time. (7) This concept of performance differs from the older meaning of the word by separating overall performance from terminal acceptability. Rather than, "was this pavement good enough prior to being replaced," this new concept of performance answers the question, "how good was it during its entire service life?" The former question of acceptability can now be answered in the context of purpose and economics.

Fundamental Assumptions

The performance-serviceability system derived by Carey and Irick from their concept of pavement performance is based on the following assumptions.

> 1. ...highways are for the comfort and convenience of the traveling public...the only valid reason for any road or highway is to serve the highway users... a good highway is one that is safe and smooth.
>
> 2. The opinion of a highway user as to how he is being served by a highway is by-and-large subjective. There is no instrument that can be plugged into a highway to tell in objective units how well it is serving the users...
>
> 3. There are, however, characteristics of highways that can be measured objectively which, when properly weighted and combined, are in fact related to the user's subjective evaluation of the ability of the highway to serve him.
>
> 4. The serviceability of a given highway may be expressed by the mean evaluation given by all highway users...

> 5. Performance is assumed to be an over-all appraisal of the serviceability history of a pavement. Thus it is assumed that the performance of a pavement can be described if one can observe its serviceability from the time it is built up to the time its performance evaluation is desired. (7)

The third and fourth assumptions anticipate the two basic measures of serviceability to be considered in the following section of this literature review.

Measurement of Serviceability

Because present serviceability is the average of the opinions of all highway users, a good estimate of the serviceability of a pavement section is obtained by sampling the opinions by means of a panel of highway users. Each member of the panel, after riding over the section either as a driver or passenger, independently rates the pavement according to an arbitrary scale. When rating a section, panelists have found it helpful to ask themselves this question: "How well would this road serve me if I were to drive my own car over roads just like it all day long today?" (7)

The numerical scale which has been used in studies by W. N. Carey, Jr. and P. E. Irick, Y. F. Nakamura, and E. J. Yoder and P. T. Milhous for rating highway pavements ranges from 0.0 to 5.0. The scale has been divided into five major divisions, and each division has been assigned a qualitative description as follows: 0.0 to 1.0 - "Very Poor"; 1.0 to 2.0 - "Poor"; 2.0 to 3.0 - "Fair"; 3.0 to 4.0 - "Good"; and 4.0

to 5.0 - "Very Good". (7, 15, 19)

In determining the present serviceability only the condition of the pavement was considered in these three studies. Extraneous factors such as condition of the ditches, right-of-way width, and highway alignment were not included in a panelist's consideration when he rated a given pavement section. Each section was assigned a present serviceability rating, PSR, equal to the arithmetic mean of the ratings given by the members of the panel.

The members of the panel should all be road users, and they should be chosen so as to represent groups of users with divergent views and attitudes. If the panel is sufficiently large and representative of all road users, the present serviceability rating of any section of highway pavement is considered to be an objective and unbiased measure of the present serviceability of that section. (7)

Carey and Irick found in their study of 64 rigid pavements and 74 flexible pavements in four states in the Middle West that certain measurements of pavement surface condition correlated well with the present serviceability rating, PSR. (7) Two statistical equations, one for rigid and one for flexible pavements, were determined in the Carey and Irick study for estimating PSR by these surface condition measurements. This method of obtaining the present serviceability of a pavement has been termed the present serviceability index, PSI. The PSI scale, because it was obtained from a regression analysis with present serviceability rating, PSR,

also ranges from 0.0 to 5.0.

These PSI equations used for estimating the present serviceability of a section include four measures of the significant factors which influence the riding condition of a pavement. Two terms indicate the amount of surface deformation. The first term, slope variance, which is determined with the AASHO profilometer, expresses the amount of longitudinal deformation. The second term, rut depth, which is significant only in the flexible equation, indicates the amount of transverse distortion. Rut depth is measured in inches at suitable intervals in the deepest part of both wheelpaths. The remaining two terms, cracking and patching, both measured manually, denote the amount of surface deterioration.

The PSI equations which were determined by W. N. Carey, Jr. and P. E. Irick are of the general form:

$$PSI = \widehat{PSR} = a - b(\log(1.0 + \overline{SV})) - c(\sqrt{C + P}) - d(\overline{RD})^2$$

where:

PSI = the present serviceability index,

$\widehat{PSR}$ = the estimated present serviceability rating,

$\overline{SV}$ = the average slope variance of both wheelpaths as measured by the AASHO Road Test longitudinal profilometer,

C = (for rigid pavements) major cracking in linear feet per 1,000 sq ft of pavement area. Major cracks are sealed cracks and those cracks which are spalled to a width of 1/4 in. for at least half their length. Measurement is made on the longitudinal or transverse projection of the crack, whichever is greater,

C = (for flexible pavements) area cracking in square feet per 1,000 sq ft of surface area which has progressed in a definite pattern joined in both directions,

P = (for rigid pavements) bituminous patching in square feet per 1,000 sq ft of pavement area. Area cracking which is awaiting maintenance may also be included in the category of patching,

P = (for flexible pavements) repair of the surface either by skin patching or by deep patching in square feet per 1,000 sq ft of surface area,

$\overline{RD}$ = average rut depth in inches measured in the center of a 4 ft span in the deepest part of the rut. This average is obtained by averaging 40 to 50 evenly spaced samples for a 1,000 ft section,

a, b, c, and d are constants whose values were determined in the regression analysis. (5)

The PSI equations determined by W. N. Carey, Jr. and P. E. Irick for rigid and flexible pavements account for 91.6 and 84.4 percent, respectively, of the variation in the rating values. (7)

Rating Panel Precision

V. F. Nakamura ascertained the minimum number of raters in a PSR panel for achieving various degrees of precision in the estimated ratings. These results, obtained in a study of 60 pavement sections, are summarized in Table 1. The study, completed in 1962, involved three rating panels of ten members each. Ten engineers from the Indiana State Highway Commission were on the first panel. The second panel consisted of ten Civil Engineering professors from Purdue University, and the third panel had on it both men and women who were not associated with the highway engineering profession. (15)

Table 1. Number of Raters Required to Estimate the Present Serviceability of a Pavement

Permissible Error ±	Number of Raters at a Probability Level of 0.05	0.10
0.3	31	21
0.4	17	12
0.5	11	8
0.6	8	5
0.7	6	4
0.8	4	3
0.9	3	2
1.0	3	2

Source: Ref. (15)

No significant difference was observed by Nakamura between the average rating of each of the two professional panels (men in the highway engineering field), and the average rating of the non-professional panel. V. F. Nakamura concluded that professional experience in the highway engineering is not important in the selection of a rater to help determine the present serviceability of a pavement. However, all the raters in the three panels had four or more years of driving experience and each rater drove over 5,000 miles per year. (15)

Other Measures of Serviceability

The serviceability-performance concept is not limited to the system of measuring present serviceability initiated by Carey and Irick. Features of the roadway surface condition other than slope variance, rut depth, cracking and patching can be used to predict the present serviceability of a pavement. Features such as the amount of scaling, spalling, blowups, D-lines, bleeding, and raveling influence the present serviceability rating of a panel. Many mechanical methods of measuring surface condition have been developed.

In an effort to correlate the various factors influencing serviceability with the methods of measuring these factors, the Highway Research Board and the American Association of State Highway Officials through the National Cooperative Highway Research Program sponsored a study to determine PSI equations relating serviceability to surface

conditions as measured by various methods. The methods included ten Bureau of Public Roads type roughometers; the University of Michigan, AASHO, and CHLOE profilometers; the Texas and South Dakota texture meters; the Kentucky accelerometer; and the Purdue tire pressure measurement device. The PSI equations that were developed are reported in the NCHRP Report 7, Comparison of Different Methods of Measuring Pavement Condition, Interim Report, by E. J. Yoder and R. T. Milhous. (19)

The PSR of each of the 50 pavement sections included in the Yoder - Milhous study was determined by a 20-member professional panel and a 10-member lay panel. The rating card used was similar to the ones used in the Carey and Irick study and in the Nakamura study, with the exception that the panelists were also asked to indicate to what degree their ratings were influenced by each of 5 factors. The factors were longitudinal distortion, transverse distortion, cracking, faulting, and surface deterioration. PSI equations were determined from a regression analysis between the present serviceability ratings and the machine and manual measurements of pavement surface condition. Some of these equations are based on the Carey and Irick model equation. Other equations are functions of machine measurements only, and do not include a cracking and patching term. The correlation coefficient for most of the equations determined was 0.85 or higher, and the standard errors of

estimate were usually less than 0.5.

The investigators found that the major factors influencing present serviceability ratings are longitudinal and transverse distortion of the pavement surface. The profilometers, roughometers, and accelerometer are well suited to measuring longitudinal distortion. The best measure of transverse distortion is still a manual measurement of rut depth. In addition to the amount of distortion, cracking, and patching, several other minor factors were found to modify the serviceability of a pavement. The magnitude of faulting between slabs and at major cracks had some influence on the ratings of rigid pavements, and the amount of bleeding appeared to be related to the serviceability of flexible and overlay pavements. The texture of the pavement as measured by the Texas and South Dakota texture meters was also found to have some effect for all pavement types. (19)

Predicting Serviceability by the AASHO P-Equations

Prior to the AASHO Road Test, the only methods for estimating the present serviceability of a highway pavement were the rating panel, PSR, and pavement surface condition measurements, PSI. Both of these methods are restricted to determining the serviceability of a pavement which has already been constructed. Neither of these methods can be used to predict the changes in serviceability with time for either existing or proposed highways.

In order to overcome these limitations, the AASHO Road Test was conducted to develop equations for predicting the present serviceability of pavements when only design characteristics and traffic loading features are known.

The specific objectives of the AASHO Road Test, as stated by the National Advisory Committee of the Highway Research Board in April, 1957, included:

> 1. To determine the significant relationships between the number of repetitions of specified axle loads of different magnitude and arrangement and the performance of different thicknesses of uniformly designed and constructed asphaltic concrete, plain portland cement concrete and reinforced portland cement concrete surfaces on different thicknesses of bases and subbases when on a pavement soil of known characteristics.
>
> 2. To develop instrumentation, test procedures, data, charts, graphs, and formulas, which will reflect the capabilities of the various test sections, and which will be helpful in future highway design, in the evaluation of the load carrying capabilities of existing highways, and in determining the most promising areas for further highway research. (3)

To accomplish these objectives, six test loops of two lanes each were constructed at Ottawa, Illinois. Each loop consisted of sections of different thicknesses of pavement. There were 468 asphaltic concrete sections and 368 portland cement concrete sections. (4)

The thicknesses of the asphatic concrete sections were 1, 2, 3, 4, 5, and 6 in. These surfaces were placed directly on the subgrade soil (a fine grained clay meeting the AASHO A-6 classification with a Group Index ranging from 9 to 13),

or on 3, 6, or 9 in. of crushed stone base, and 4, 8, 12, or 16 in. of sand-gravel subbase. Flexible pavement sections having all possible combinations of these thicknesses were included in the Road Test. (5)

"The thicknesses of the portland cement concrete sections were 2 1/2, 3 1/2, 5, 6 1/2, 8, 9 1/2, 11, and 12 1/2 inches. Some were placed directly on the subgrade soil; others were placed on 3, 6, or 9 inches of sand-gravel subbase." Each design was used with both plain and reinforced concrete. (5)

Test traffic was driven over each lane of five of the six loops for slightly more than two years. Loop 1 did not receive test traffic; instead, it was reserved for special environmental tests. Each test traffic lane received 1,114,000 axle load applications. Steering axles were not counted as producing load applications.

Ten types of trucks, each having a different axle load and axle configuration (single or tandem axle) were used as test vehicles. The axle loads of the test vehicles ranged from 2 to 22.4 kips for the single axles and from 24 to 48 kips for the tandem axles. As a result, the gross weight of the vehicles ranged from 4 to 108 kips. However, trucks of only one given type of axle (single or tandem) and weight of axle were driven on any given lane.

The rigid and the flexible pavement sections were considered separately in the AASHO Road Test analyses. The average initial serviceability, C_1, for all the pavements of a given type was determined in the initial stage of the

test, by measuring the amount of cracking, patching, rut depth, and slope variance, and then using the Carey and Irick PSI equations.

The present serviceability index of each test section was subsequently calculated every two weeks by these same PSI equations. A test section was considered to have failed when the specified terminal level of serviceability, C2, was reached. The total number of accumulated axle applications, Rho, was recorded for each section that reached failure. An equation was developed for each pavement type (rigid or flexible) correlating Rho with the thickness of the pavement and the weight and type (single or tandem) of axle loads to which the pavement was subjected.

The equation for Rho was based upon the relationship that Rho increases with thicker pavements or if a tandem axle is used rather than a single axle, while Rho decreases if the axle load is increased. The general equation for Rho is:

$$\rho = \frac{a\ (D + 1.0)^b\ (L2)^c}{(L1 + L2)^d}$$

where:

ρ = Rho = the total number of accumulated axle applications to a PSI equal to C2,

D = the effective thickness of the pavement (termed SN or structural number in the case of flexible or overlay pavements),

L1 = the axle load,

L2 = an axle coding factor equal to 1.0 when the axle is single and 2.0 when the axle is tandem, and

a, b, c, and d are constants determined in the two separate regression analyses for rigid and flexible pavements.

Of the several model equations considered for predicting serviceability, the following expression provided the best fit of the field data collected at the AASHO Road Test.

$$P = \widehat{PSI} = C1 - (C1 - C2)(W / \rho)^{\beta}$$

in which $C1 \geq P \geq C2$,

and where:

P = the present serviceability as estimated by the number of applications of a given axle load on a given pavement,

$\widehat{PSI}$ = the estimated present serviceability index of the given pavement section,

C1 = the average initial serviceability of all the pavements of this type,

C2 = the selected terminal serviceability level,

W = the number of accumulated axle applications at the time P is calculated,

ρ = Rho = the total number of accumulated axle applications to the time the pavement reaches the terminal serviceability of C2,

β = Beta = an exponent which determines the general shape of the serviceability trend.

An equation was found to express Beta as a function of pavement thickness and the weight and type of axle load applied. Because Beta is usually close to one, the graph of P tends to approximate a straight line.

The equations which were developed at the AASHO Road Test on the basis of this model equation are commonly referred to in the literature as the AASHO Performance

Equations. However, these equations actually predict the present serviceability of a pavement and only indirectly its performance. Therefore, these equations will be referred to throughout this report as the AASHO P-equations.

The AASHO P-equation for rigid pavements is as follows:

$$P = 4.5 - (4.5 - 1.5)(W / \rho)^{\beta}.$$

As explained in the P-equation model:

P = the present serviceability as estimated by the number of applications of a given axle load on a given pavement,

4.5 = the average initial serviceability of all the rigid pavements in the Road Test,

1.5 = the selected terminal serviceability level,

W = the number of accumulated axle applications at the time when P is calculated,

ρ = Rho = the total number of accumulated axle applications to the time the pavement reaches the terminal serviceability of 1.5, and

β = Beta = the exponent which determines the general shape of the serviceability trend.

Rho is estimated by the equation:

$$\rho = \frac{(10.0)^{5.85}\ (D + 1.0)^{7.35}\ (L2)^{5.22}}{(L1 + L2)^{4.62}},$$

and Beta is given by the equation:

$$\beta = 1.0 + \frac{4.63\ (L1 + L2)^{5.20}}{(D + 1.0)^{8.46}\ (L2)^{3.52}},$$

where:

L1 = the total axle load in kips on either a single or tandem axle,

L2 = 1.0 for a single axle, and 2.0 for a tandem axle, and

D = the effective thickness of pavement, in inches.

Graphs of Rho and Beta as functions of effective thickness for fixed values of L1 = 18.0 kips and L2 = 1.0 are given in Appendix A.

The P residual summary determined at the AASHO Road Test for the rigid P-equations is as follows: a correlation index, r^2, of 16 percent, and a correlation coefficient, r, of 0.40, and a root mean square residual of 0.24. "The low correlation index is due in part to the relatively narrow spread in the log W values." There is approximately 90 percent confidence that PSI will be found between P $\pm$0.34 . (4)

Two sets of equations were determined, at the AASHO Road Test, for flexible pavements. One set, termed the unweighted equations, were evolved using the actual values of W, in the same manner as the rigid equations were developed. The other set, termed the weighted equations, are based on values of W which have been modified by a seasonal weighting function. The rationale behind the weighted equations is discussed under "Climatic Factors" in this review of literature.

The equation for P is the same for both the weighted and the unweighted set.

$$P = 4.2 - (4.2 - 1.5)(W / \rho)^{\beta}$$

in which P, W, ρ, and β correspond to the same terms in the rigid P-equation. The differences between the weighted and

unweighted equations are in the relationships for estimating Rho and Beta. For the unweighted case Rho is estimated by the equation:

$$\rho = \frac{(10.0)^{6.16}\ (SN + 1.0)^{8.94}\ (L2)^{4.17}}{(L1 + L2)^{4.54}} \quad ;$$

and for the weighted case:

$$\rho = \frac{(10.0)^{5.93}\ (SN + 1.0)^{9.36}\ (L2)^{4.33}}{(L1 + L2)^{4.79}} \quad .$$

For the unweighted situation Beta is given by the equation:

$$\beta = 0.4 + \frac{(0.083)(L1 + L2)^{4.37}}{(SN + 1.0)^{8.73}\ (L2)^{4.87}}$$

and for the weighted assumption Beta equals:

$$\beta = 0.4 + \frac{(0.081)(L1 + L2)^{3.23}}{(SN + 1.0)^{5.19}\ (L2)^{3.23}}$$

where:

L1 = the total axle load in kips on either a single or tandem axle,

L2 = 1.0 for a single axle, and 2.0 for a tandem axle, and

SN = the structural number = the effective thickness of the pavement, in inches.

The effective thickness is determined by the equation:

$$SN = \sum_{i} (Ai)(Di)$$

where:

Ai = a coefficient reflecting the relative strength of the component layer, i; and

Di = the thickness in inches of the layer, i.

The P residual summary for the weighted and unweighted

flexible equations are as follows: correlation indices, r^2, of 0.48 and 0.70; correlation coefficients, r, of 0.69 and 0.84; and root mean square residuals of 0.47 and 0.54, respectively. There is approximately 90 percent confidence that PSI will be observed between P $\pm$ 1.1 for the unweighted flexible equation, and P $\pm$ 0.9 for the weighted equation. (4)

The weighted equations were considerably better than the unweighted equations for Rho and Beta when used for predicting the present serviceability of the flexible pavement sections included in the AASHO Road Test. This greater precision was because the weighted equations took into account the seasonal change in the soil support provided by the subgrade.

Climatic Factors

The AASHO Road Test was conducted near Ottawa, Illinois, which is about 80 mi southwest of Chicago. Ottawa is located on an east-west line which runs about 13 mi south of Hammond, Indiana, and about 26 mi north of Fort Wayne.

"The annual precipitation at the site averages about 34 in., of which 2.5 in. occurs as 25 in. of snow. The climate is typical of that found throughout much of the northern United States." The depth of frost penetration is 25 in., which is between 5 and 10 in. deeper than most of Indiana. (3)

It was observed at the Road Test that the same load had lesseffect on a flexible pavement if applied during the frozen winter months, than if applied during the spring

break-up. This effect was not noticeable for the rigid pavement sections.

In order to account for this effect the weighted flexible P-equation was developed. The number of accumulated axle applications, Wt, for a given period, t, was multiplied by a seasonal weighting factor, Qt, for that period. In the same way that the unweighted equations were obtained from a plot of P versus W, the weighted equations for P, Rho and Beta were developed by plotting P against $Wwt = \sum_t (Qt)(Wt)$.

"The use of seasonal weighting factors increased the correlation index of the flexible (P-equation) from 48% to 70%, and reduced the mean residuals by 15%." (4) The seasonal weighting factor was determined from the average deflection of several pavements under a 6-kip tandem wheel load. This weighting function is defined by:

$$Qt = \left[\frac{2\ Dt - Ds}{\overline{D}}\right]^2$$

where:

Qt = the seasonal weighting factor for the period, t;

Dt = the estimate of the average deflection of 8 flexible sections in loop 1 when subjected to a 6-kip tandem wheel load during the period, t;

Ds = the smoothed deflection for the period preceding the index period, t; and

$\overline{D}$ = the average Dt during the two year AASHO Road Test.

The division by $\overline{D}$ makes Qt a dimensionless factor. However, it also makes the function strictly applicable only to the site at which the deflection data were gathered. (4)

The use of a seasonal weighting function is necessitated in the event that either the subgrade support, the number of axle applications, or the traffic composition varies significantly among the seasons of the year. The seasonal weighting function has been used to determine the regional factor, RF. The purpose of the regional factor is to extend the applicability of the weighted AASHO flexible P-equations to other parts of the country by typifying the weather conditions at any given location. The RF is the mean value of the seasonal weighting factors determined at the given location, i.e.

$$RF = \left(\sum_{t} Qt \right) / t \ .$$

The regional factor obtained at Ottawa, Illinois, for the two-year AASHO Road Test equals 1.2. (5)

The seasonal weighting factors for certain typical conditions which can be used to estimate the regional factor are as follows:

Roadbed soil frozen
(5 in. depth or more) . . . . . 0.2 to 1.0

Roadbed soil dry
(summer and fall) . . . . . 0.6 to 1.5

Roadbed soils saturated
(spring break-up) . . . . . 4.0 to 5.0. (1)

These values were obtained by correlating the weather conditions as experienced at the Road Test during the period, t, with the seasonal weighting function, Qt, obtained from deflection measurements. Whether the correlation is valid throughout the remainder of the country is yet to be established.

The seasonal weighting factor or the regional factor is used in solving the weighted flexible P-equation by computing either:

$$Wwt = \sum_t (Qt)(Wt) \text{ ; or}$$

$$Wwt = (RF)(\sum_t Wt) = (RF)(W)$$

where:

Wwt = the total number of weighted axle applications;

Qt = the seasonal weighting factor during the period, t;

RF = the regional factor;

Wt = the number of axle applications during the period, t; and

W = the total number of axle applications.

Then, Wwt is substituted for W in the P-equation and the equation is solved for the estimated present serviceability.

Effective Thickness of a Pavement

The AASHO equations for Rho and Beta are functions of the effective thickness. The effective thickness concept attempts to take into account the entire pavement system. The factors considered include the thickness of the component layers: subbase, base, and surface; the materials of construction of these layers in regard to both their relative strength and durability; and the support provided by the subgrade.

The effective thickness, D, of a rigid pavement depends

primarily on the thickness, D2, of the concrete slab. However, if a subbase is not provided, then the effect of the subgrade is significant.

The effective thickness, SN, of flexible and overlay pavements depends on the thickness, Di, of each component layer, i. Each layer is weighted by a strength coefficient, Ai, which reflects the relative cohesion, stability, and bearing values of the material in question. The relationship for the effective thickness of flexible and overlay pavements is:

$$SN = \sum_{i} (Ai)(Di).$$

The strength coefficients for the construction materials used at Ottawa were determined as part of the AASHO Road Test regression analysis in which the P-equations were determined. The strength coefficients for various component layers are:

Surface Course -	A1
Road mix (low stability)	0.20
Plant mix (high stability)	0.44
Sand asphalt	0.40

Base Course -	A2
Sand gravel	0.07
Crushed stone	0.14
Water-bound macadam	0.15 - 0.20
Lime-treated	0.15 - 0.30
Sand asphalt	0.30
Bituminous-treated	0.34
Cement-treated	0.15 - 0.23
Old bituminous concrete surface	0.14 - 0.24
Portland cement concrete	0.40 - 0.50

Subbase -	A3	
Sandy gravel	0.11	
Sand or sandy clay	0.05 - 0.10	(5)

However, these strength coefficients are for use with the weighted flexible P-equation only. With the unweighted equation, the strength coefficients should be slightly lower.

In the case of flexible or overlay pavements, the soil support provided by the subgrade can not be neglected. A method of modifying the weighted AASHO flexible P-equation to take into account the strength of the subgrade has been determined by the AASHO Design Committee. (5) This method makes use of a soil support scale which has been correlated with various strength tests including CBR and P. (1, 2)

Three facts concerning the AASHO P-equations are of special importance to all studies or design procedures using these equations. First, the pavement sections were specially constructed for the AASHO Road Test, on a uniform subgrade of A-6 soil, in a geographically small area with one set of weather and climatic conditions. Second, the pavements received a lifetime of traffic loading in conjunction with only two years of weathering. Third, trucks of only one axle type and weight were driven on a given pavement section. This fact precludes the use of Road Test data to determine the effect of the interactions between cars and trucks of varying weights on pavement behavior. These three significant areas of discrepancy between Road Test conditions and

actual pavement, environmental, and traffic features of highways serve to increase the precision of the AASHO P-equations but limit their direct applicability in other parts of the country.

However, a method has been found by F. H. Scrivner and H. C. Duzan to extend the AASHO P-equations to a mixed traffic condition. This method makes use of equivalence factors. (18)

Equivalence Factors

The AASHO P-equations were derived for test pavements receiving axle applications of only one type (single or tandem) and one load. Because this is not the case for actual highways, it was necessary that either some means be found to evaluate A, Rho, and Beta for a mixed traffic condition, or else, some means be found to reduce the axle loads to one single "equivalent" axle load.

The first method, referred to as mixed traffic theory, leads to an integral which can not be readily evaluated, and hence is difficult to use. The second method, called equivalence traffic theory, converts all loads to equivalent 18-kip single axle loads. It is much simpler to use than mixed traffic theory. Generally, the two methods yield similar results. (18)

An equivalence factor, Eri, is assumed to be a measure of the destructive capability of an axle load of a given weight and type category, i, compared to an 18-kip single

axle standard. Actually, an equivalence factor is the ratio of the total number, W18, of 18-kip single axle load applications, to the total number, Wi, of axle load applications of a given weight and type category, i, necessary to reach the same terminal present serviceability on a given type and thickness of pavement, i.e.:

$$EFi = W18 / Wi.$$

With the use of equivalence factors, the AASHO P-equations can be solved directly. Rho and Beta are reduced to functions of just one variable, effective thickness, since L1 is set equal to 18.0 kips and L2 to 1.0. The total number, W, of accumulated axle loads equals the summation of the number, Wi, of axle loads of each weight and type category, i, times its appropriate equivalence factor, EFi. The formula is:

$$W = \sum_{i} (Wi)(EFi).$$

EFi is a function, not only of the weight of the axle and its type (single or tandem), but also of the type of pavement (rigid or flexible) and the effective thickness of the pavement (D or SN), as well as the terminal level of present serviceability. These relationships become apparent when the origin of equivalence factors is more closely investigated. In the determination of equivalence factors the AASHO P-equations are used to obtain the number of axle applications that have equivalent destructive capabilities.

The derivation begins with the basic AASHO P-equation:

$$P = C1 - (C1 - C2)(W / \rho)^{\beta}.$$

An expression for W is obtained by rearranging the terms, and then raising both sides of the equation to the $(1.0/\beta)$ power. This expression is solved twice, once for W18 and then again for Wi. The equivalence factor, EFi, for a given load and axle arrangement, i, is the ratio of W18 to Wi:

$$EFi = \frac{W18}{Wi} = \frac{(\rho 18)((C1 - Pt) / (C1 - C2))^{(1.0/\beta 18)}}{(\rho i)((C1 - Pt) / (C1 - C2))^{(1.0/\beta i)}}$$

where:

EFi = the equivalence factor for axle load and type, i;

W18 = the total number of 18-kip single axle load applications to a terminal serviceability of Pt;

Wi = the total number of applications of the axle load and type, i, to the same serviceability, Pt;

$\rho 18$ and $\beta 18$ = the values of Rho and Beta when L1 = 18.0 kips and L2 = 1.0, and D or SN = the effective thickness considered for the given type of pavement;

ρi and βi = the value of Rho and Beta when L1, L2, and D or SN = the appropriate values for the axle load and type, i, and the effective thickness and pavement type considered; and

Pt = the terminal level of present serviceability of the pavement.

The AASHO Interim Design Guides list equivalence factors as a function of axle load for both single and tandem axles at terminal serviceabilities of 2.0 and 2.5; for effective thicknesses, D, of rigid pavements equal to 6, 7, 8, 9, 10, and 11 in.; and effective thicknesses, SN, of flexible pavements equal to 1, 2, 3, 4, 5, and 6 in. (1, 2)

Equivalence traffic theory permits using the AASHO

P-equations for predicting the present serviceability of a highway pavement where both the traffic distribution and the pavement design are known and the equations for Rho and Beta are applicable. If the present serviceability of a pavement is known throughout the service life of the pavement, the question of how well the pavement served the traffic can be answered.

PROCEDURE

With the pavement serviceability - performance concept as the foundation and the AASHO P-equations as the framework, a method was developed in this study for comparing alternate pavement designs. The AASHO P-equations are expressions which empirically relate the changing present serviceability of a pavement with the cumulative number of axle load applications. These equations are commonly denoted in the literature as the AASHO Performance Equations. However, to avoid confusion with the performance equations which were developed in this study of Indiana highway pavements, the AASHO performance equations are referred to as the AASHO P-equations throughout this study.

The general procedure of this study is summarized in the following steps:

1. The AASHO P-equations were modified to adequately predict the present serviceability of rigid, flexible, and overlay pavements in Indiana.
2. A mathematical equation was developed to estimate the performance of highways for various traffic conditions.
3. A technique was devised for comparing alternate

pavement designs for any given location in Indiana. The criteria for selection are the performance and cost of each design thickness for the service life of the pavement.

The design comparison method developed in this study is applicable in all parts of the country where the AASHO P-equations have been verified, or modified if necessary.

Modification of Serviceability Equations

The modification of the P-equations was accomplished by comparing the present serviceability of 160 sections of highway pavement as predicted by the AASHO equations to the actual serviceability that was observed at a known point in the service history of each study section. The number of sections in this study represented about 30 percent of the total number of test sections included in the AASHO Road Test main factorial analysis.

Actual Present Serviceability

The present serviceability of each section in this study had been measured in one of three previous investigations: F. M. Holloway in the summer of 1955; V. F. Nakamura in October, 1961; and E. J. Yoder and R. T. Milhous in August, 1963. The number of sections borrowed from each of these investigations is shown in Table 2.

The data from the latter two studies were already in the form of present serviceability ratings. However, F. M.

Table 2. Summary of Study Sections Located in Indiana

Investigator	Serviceability Measurement	Number of Pavement Sections		
		Rigid	Flexible	Overlay
Holloway 1955 (10)	PSI (Roughometer)	61	24	0
Nakamura 1961 (15)	PSR (30 Member Panel)	10	17	16
Yoder-Milhous 1963 (19)	PSR (30 Member Panel)	9	15	8
Totals		80	56	24

Holloway had used the Indiana (Purdue) roughometer to measure the amount of pavement distortion displayed by each one of his 115 sections. These roughometer measurements and the Yoder-Milhous equations for predicting the present serviceability using the Indiana roughometer were employed to compute the present serviceability index, PSI, of each of Holloway's sections. The relationship for rigid pavements is:

$$PSI = \widehat{PSR} = 5.09 - (0.025)(R);$$

and the equation for flexible pavements is:

$$PSI = \widehat{PSR} = 4.79 - (0.015)(R);$$

where:

PSI = the present serviceability index of the section,

$\widehat{PSR}$ = the estimated present serviceability rating of the section,

R = the number of inches of roughness per mile as measured by the Indiana (Purdue) roughometer.

The correlation coefficient, r, is 0.90 for the rigid equation and 0.91 for the flexible equation. The standard errors of estimate, S_E, for the rigid and flexible equations are 0.42 and 0.28, respectively. (19) Therefore, there is a 90 percent probability that the PSR will be found within PSI $\pm$0.8 for a rigid pavement section and PSI $\pm$0.6 for a flexible section.

Nakamura and Yoder-Milhous determined the present serviceability of their respective sections by means of a 30-member rating panel. Nakamura discovered that a 30-member panel estimates the present serviceability within

± 0.3 of the true present serviceability at the 5 percent level of significance. (15, 19)

The 160 sections included in this study were located throughout the entire State of Indiana. Over 57 percent of the 92 Indiana counties were represented by one or more sections, and more than one third contained two or more sections. The Indiana State Highway Commission has divided the state into 6 maintenance districts. A breakdown of the distribution of the sections by ISHC maintenance districts is shown in Table 3.

Serviceability data were available for a total of 224 sections from the three research studies. However, 64 sections were eliminated from this analysis for one or more of the following reasons:

1. The section was not part of the Indiana State Highway system;
2. Road life data were not available because the section was located within the corporate limits of a city;
3. The section was not homogeneous with regard to the variables considered; and/or
4. The exact location of the section could not be determined.

The sections which were considered include three pavement types (rigid, flexible, and overlay), and a wide range of present serviceability and traffic volumes.

Table 3. Distribution of Pavement Study Sections by ISHC Maintenance Districts

District	Number of Sections			
	Rigid	Flexible	Overlay	Total
La Porte	7	7	8	22
Fort Wayne	6	1	0	7
Crawfordsville	32	38	16	86
Greenfield	10	0	0	10
Vincennes	15	3	0	18
Seymour	10	7	0	17
Totals	80	56	24	160

Predicted Present Serviceability

The serviceability of a highway pavement section can be predicted from the AASHO P-equations providing ρ, β, and the accumulated number of axle applications, W, either are known or can be estimated. The general form of the AASHO P-equations is:

$$P = C1 - (C1 - C2)(W / \rho)^{\beta}$$

where:

P = the present serviceability as estimated by the number of applications of a given load on a given pavement,

C1 = the average initial serviceability of all the pavements of the given type,

C2 = the selected terminal serviceability level,

W = the number of accumulated axle application at the time when P is calculated,

ρ = Rho = the total number of accumulated axle applications to the time the pavement reaches the terminal serviceability level of C2, and

β = Beta = an exponent which determines the general shape of the serviceability trend.

Rho and Beta can be approximated if the pavement design is available and if the equation for Rho and the equation for Beta determined at the AASHO Road Test are assumed to be applicable. The general form of the equation for Rho is:

$$\rho = \frac{a\ (D + 1.0)^{b}\ (L2)^{c}}{(L1 + L2)^{d}}$$

and the expression for Beta is of the form:

$$\beta = e + \frac{f\ (L1 + L2)^{g}}{(D + 1.0)^{h}\ (L2)^{i}}$$

where:

D = the effective thickness of the pavement section (in the case of flexible and overlay pavements the effective thickness is abbreviated as SN),

L1 = the total axle load in kips on either a single or a tandem axle,

L2 = 1.0 for single axles, and 2.0 for tandem axles, and

a, b, c, d, e, f, g, h, and i are constants whose values were determined in the AASHO Road Test regression analysis.

Rho and Beta are parametric equations, i.e. different functions of the same variables. The parameters are axle load, L1; axle type, L2; pavement type, rigid or flexible (resurfaced pavements are included with flexible pavements; if the resurfacing is done over an old rigid pavement, it is called an overlay); and effective thickness, D or SN. The use of equivalence traffic theory permits the reduction of the traffic stream to one equivalent axle type and load. Without this theory the AASHO P-equations could not be applied to mixed traffic conditions. (18)

All the axle load applications are expressed in terms of equivalent numbers of 18-kip single load applications. Because L1 is set equal to 18.0 kips and L2 equals 1.0, Rho and Beta are simplified to functions of effective thickness only, for each pavement type.

The effective thickness is based on the relative contribution of each layer in providing for the total load carrying capacity of the pavement system. The effective thickness was computed for each rigid, flexible, and

overlay section in this study. The thickness and construction material data for the various component layers of each pavement section were obtained from the road life records of the Indiana State Highway Commission.

The effective thickness, D, of each of the portland cement concrete sections was simply approximated by the thickness of the slab, D2. The only modification for the rigid pavements was for sections having thickened-edge slabs. In these cases, a uniform effective thickness was calculated by means of the Westergaard equation for corner loading. The effective thicknesses for 9 - 6 - 9 and 9 - 7 - 9 slabs are 7.1 and 7.7 in., respectively. (9) All the rigid pavements included in this study are portland cement concrete pavements referred to by the ISHC as type 7021.

The effective thickness, SN, of each of the flexible and overlay pavements was computed from the strength coefficient, Ai, and the thickness, Di, of each of the layers which comprises the pavement section. A strength coefficient reflects the relative cohesion, stability, and bearing value of the material. These coefficients were obtained from the values determined at the AASHO Road Test for similar materials. (4) The effective thickness of a flexible or overlay pavement is calculated by the relationship:

$$SN = \sum_{i} (Ai)(Di)$$

where:

SN = the effective thickness of a flexible or overlay pavement,

Ai = the strength coefficient of the layer, i, and

Di = the thickness, in inches, of the layer, i.

The layers, i, are usually the surface, 1; the base, 2; and the subbase, 3. A resurfaced pavement may have more than 3 layers.

Seven types of bituminous pavement are represented by the study sections of this report. The flexible pavement types are 4231, 4253, 6201, 6202, and 6221. A 4231 is the ISHC designation for a pavement of mixed bituminous surfacing with a combined thickness of surface and base greater than 7 inches. A 4253 is a mixed bituminous stabilized gravel. A 6201 is a bituminous concrete, type B. A 6202 is a mixed bituminous concrete on a non-rigid subbase. A 6221 is a rock asphalt on a non-rigid subbase.

The overlay pavement types in this study are 6706 and 6726. A 6706 is a hot asphalt concrete on a rigid subbase, while a 6726 is a rock asphalt pavement on a rigid subbase.

In the case of flexible and overlay pavements the strength of subgrade can not be neglected as it customarily is with rigid pavements. A modification of the AASHO flexible P-equation reflecting the bearing capacity of the subgrade was determined from Chart 400-1 of the AASHO Interim Design Guide for Flexible Pavement Structures. (1) This modification is made directly to the effective thickness, SN,

because the subgrade is an integral part of a flexible or overlay pavement system. The set of equations for determining the modified effective thickness, SNmod, is as follows:

$$X1 = 11.5\ (S - 3.0)$$

$$X2 = \frac{-130.0 + \sqrt{16,900.0 - 55,600.0\ (1.095 - SN)}}{2.78}$$

$$X3 = X1 + X2$$

$$SNmod = (1.39 \times 10.0^{-4})(X3)^2 + (0.013)(X3) + (1.095)$$

where:

SN = the effective thickness of the surface, base, and subbase of either a flexible or overlay pavement;

S = the soil support value (or factor) of the subgrade; and

SNmod = the effective thickness of the entire pavement system including the effect of the subgrade.

The modified effective thickness was used to determine the values of Rho and Beta which were then substituted into the AASHO flexible P-equation to predict the present serviceability of each of the flexible and overlay pavement sections included in this study.

In order to overcome the inherent limitations of the AASHO soil support correlation, the idea of a soil rating panel was conceived in this study of Indiana pavements. Six Civil Engineers, well acquainted with the engineering properties and behavior of the soils of Indiana, were asked to serve on the panel. Each panelist gave his opinion of the relative effect of the major soil types of Indiana on

flexible pavement performance when a highway is built on a subgrade consisting of one of the soils.

The major soil types of Indiana have been delineated on the map entitled "Engineering Soil Parent Material Areas of Indiana - 1950." The soils of Indiana are divided into 17 major soil units on this map. These soil units are based upon origin and either parent material or landform.

The major soil unit, "Water Transported Sands," was further subdivided for the purpose of this study into the "Kankakee Sands" and "Sands Except the Kankakee Sands." Because the soils within a given unit are reasonably similar in their behavior as subgrade materials, a single soil performance rating is sufficiently representative of the soils within a given unit.

The rating scale used by the panelists ranged from 0.0 to 10.0. The scale was categorized into five intervals which represent qualitative degrees of pavement behavior on these subgrades: 0.0 to 2.0 - "Very Poor"; 2.0 to 4.0 - "Poor"; 4.0 to 6.0 - "Average"; 6.0 to 8.0 - "Good"; and 8.0 to 10.0 - "Very Good".

Each member of the panel independently evaluated the relative performance of the 18 major soil units in Indiana. A copy of the instructions to the raters is included in Appendix B.

The soil ratings of the panel were used to determine the soil support factor for each major soil unit. The modified effective thickness for each flexible and overlay

section was determined from the average soil support factor associated with the major soil units under each pavement section.

To summarize the steps in obtaining values for Rho and Beta:

1. For rigid pavements, the effective thickness, D, is the slab thickness, in inches, with a possible modification due to thickened-edge design.
2. For flexible pavements, the basic effective thickness, SN, is a linear combination of the thicknesses of the component layers, with strength coefficients. SN is modified by a soil support factor. This modified effective thickness, SNmod, is used in either the weighted or unweighted equations for Beta and Rho.
3. Rho18 and Beta18 are calculated from the appropriate equations for the pavement type, with the effective thickness ss described above, and with L1 = 18.0 kips and L2 = 1.0.

When Rho and Beta are expressed in terms of an 18-kip single axle load, then the total number of axle applications, W, has to be expressed in terms of 18-kip equivalent axle loads. The W for each pavement section was estimated from the average daily traffic, ADT; a measure of the traffic composition, percentage of trucks in the total traffic stream; and the number of years, Y, from the time of construction to the time of rating.

The ADT for each section was obtained from the report entitled: "Sufficiency Ratings - 1966, Indiana State Highways." If a given section had been divided into several subsections in the sufficiency study, and if the subsections had different ADT volumes, then the weighted average ADT was calculated. This average was weighted according to the length of highway for each traffic volume recorded.

A growth factor of 6 percent per year was used in determining the average volume of traffic on each section from the time of its construction to the time of its rating. The formulas used were:

$$ADTa = \frac{ADTb + ADTc}{2.0}$$

$$ADTb = \frac{ADT65}{(1.0 + r)^{(65 - b)}}$$

$$ADTc = \frac{ADT65}{(1.0 + r)^{(65 - c)}}$$

where:

ADTa = the ADT of the section averaged over the period prior to rating;

ADTb = the ADT when the section was built, in the year, b;

ADTc = the ADT when the section was rated, in the year, c;

ADT65 = the '65 ADT determined from the "Highway Sufficiency Study" (for one direction); and

r = the growth rate of traffic per year expressed as a decimal fraction.

A sensitivity analysis was performed to evaluate the effects

on the predicted serviceability if ADT growth factors of 4 and 8 percent were assumed rather than 6 percent.

The year of construction of each section was determined from the road life records of the Indiana State Highway Commission Planning Department. In the event the construction year coincided with the rating year, traffic was assumed to have gone over the section for 180 days. Only a slight loss in precision resulted from this approximation, because the most important variable influencing the present serviceability is the initial serviceability of the pavement and not the traffic volume when the age of the pavement is two years or less.

The traffic composition for each section was estimated from data gathered at 22 loadometer stations every year for three years. The analysis of this data permitted the development of equivalence coefficients. The results and implementation of this approach are further discussed under the heading entitled "Equivalence Coefficients" in the section on results.

When the AASHO flexible P-equations are used to predict the present serviceability of a highway pavement section, the following possibilities exist for the determination of the cumulative number of 18-kip equivalent axle applications, W. If it is assumed that the conditions are similar to those at Ottawa, Illinois,

1. the unweighted flexible P-equation with no modification

to W, or

2. the weighted flexible P-equation with either the seasonal weighting factors, Qt, or the regional factor, RF, as determined at the AASHO Road Test

may be used. When a variation in climatic factors is to be included, the weighted equation should be employed. This equation is adapted for the area in question by

3. a regional factor estimated from the general knowledge of the climatic conditions of the region, or

4. seasonal weighting factors determined by deflection measurements in the area, or a regional factor derived from these seasonal weighting factors.

Although the fourth method is the most direct, it requires several years of deflection measurements. Therefore, only the first three methods were employed in this study of Indiana pavements to determine the number of 18-kip equivalent axle applications, W, for each section.

Indiana Serviceability Equations

The Indiana rigid, flexible, and overlay serviceability equations were developed in this study so that the present serviceability of highway pavements throughout the state can be predicted with known limits of precision. The Indiana equations are based on the AASHO Road Test equations for Rho and Beta, and linear modifications of the AASHO rigid and

flexible P-equation.

In each of the three analyses, a regression equation was determined relating the present serviceability predicted by means of the AASHO P-equations and the actual present serviceability rating of each section as determined by either Holloway, Nakamura, or Yoder-Milhous. The regression equations are of the form:

$$P_{Ind_{ij}} = \widehat{PSR_{ij}} = A_j + B_j\left[P_{ij}\right]$$

where:

$P_{Ind_{ij}}$ = the present serviceability of the Indiana pavement section, i, predicted from knowledge of its traffic loadings and pavement design, for the type of pavement, j (rigid, flexible, or overlay);

$\widehat{PSR_{ij}}$ = The estimated present serviceability rating for the pavement, i, of type, j;

P_{ij} = the present serviceability of the pavement, i, predicted by using the AASHO P-equation for the pavement type, j;

A_j and B_j are the constants determined in the regression analysis.

The values of A_j and B_j were first determined using a least-squares regression analysis. The equations are:

$$A_j = \overline{PSR_j} - B_j\left[\overline{P_j}\right] \quad ; \text{ and}$$

$$B_j = \left[\frac{\sum_i (P_{ij} - \overline{P_j})(PSR_{ij} - \overline{PSR_j})}{\sum_i (P_{ij} - \overline{P_j})^2}\right].$$

Any regression equation for P_{Ind} which is accepted must

meet the constraint that, whever P_{Ind} equals C2, W equals Rho. This condition is necessary because Rho has been defined as the number of axle applications which produces a serviceability level of C2. This constraint is fulfilled by the least-squares equation determined for the Indiana rigid pavement sections, but not for the flexible and overlay sections. For these pavement types, A_j and B_j were determined by the equations:

$$A_j = \overline{PSR_j} - B_j (\overline{F_j})$$

$$B_j = \left[\frac{\overline{PSR_j} - C2}{\overline{F_j} - C2} \right]$$

The flexible and overlay regression equations for P_{Ind} which were determined from the latter equations for A_j and B_j were forced to fulfill the constraint that P_{Ind} = C2, if and only if W equals Rho. The regression technique of Sandor Popovics was used to test the precision of these equations. (18) The precision of the rigid equation was tested by the standard equations for correlation coefficient and standard error of estimate for a least-squares regression analysis.

The AASHO flexible F-equation (weighted and unweighted) was used to predict the serviceability of both original and resurfaced pavements. This same equation was used in the overlay pavement analysis to predict the serviceability of bituminous resurfaced rigid pavements. Composite pavements were not included in this study.

Derivation of Performance Equations

The average serviceability displayed by a pavement over its service life was used as a practical measure of its performance. This gauge of performance had been suggested by W. N. Carey, Jr. and P. E. Irick in their development of the pavement serviceability-performance concept. (7) The average serviceability was selected over other estimates of performance, such as the slope of the serviceability-versus-time curve, the reciprocal of Beta, etc., because this measure is easy to calculate and interpret, and it is in the same units as the present serviceability rating, PSR, and the present serviceability index, PSI. The equations for average serviceability or performance were obtained by integrating the Indiana serviceability equations with respect to W. The area under each curve was divided by the total number of equivalent axle applications to obtain the average serviceability for that pavement classification. The relationship:

$$Pa = \frac{\int_{W=Wi=0}^{W=Wt} P_{Ind}\, dW}{Wt - Wi}$$

becomes, after integrating and substituting:

$$Pa = \left[\frac{Pt + (A)(\beta 18)}{\beta 18 + 1.0}\right]$$

Where:

Pa = the performance or average serviceability of a given section of pavement during its service life,

P_{Ind} = the predicted serviceability as a function of W

and pavement design,

W = the cumulative number of equivalent 18-kip single axle load applications,

Wi = 0 = the initial value of W,

Wt = the value of W when P_{ind} equals Pt,

Pt = the terminal level of serviceability,

A = the value of the appropriate Indiana serviceability equation when W equals Wi, and

β_{18} = the exponent of the appropriate Indiana serviceability equation as a function of effective thickness of the given pavement.

The complete derivation of this equation is given in Appendix C

Development of Technique

A technique was devised for incorporating a measure of over-all performace into pavement design. A preliminary step in this procedure was the development of the Indiana serviceability equations and the performance equations.

A wide range of applicability was achieved by the choice of variables which have a predictable effect on performance and which reflect the data normally available to the designer concerning the highway location and expected traffic. Calculability of both performance and cost was the basis for the selection of the design parameters. The cost functions chosen were those commonly in use.

For each pavement type, the performance was calculated for twelve effective thicknesses and all reasonable choices of terminal serviceability. Comprehensive tables of these values were prepared. Nomographs were designed to eliminate

the need for excessive computations.

An incremental performance-to-cost ratio was selected as the simplest means of determining the optimal design of those considered for the given highway location. Performance and cost data are both in the form of average annual values. This approach adequately solved the problem of compatibility of units.

RESULTS

The results of this research study extend the applicability of equivalence traffic theory, the AASHO Road Test P-equations, and the AASHO Interim Guides for Design. (1, 2, 3, 4, 5, 18)

1. Equivalence traffic theory was extended by the development of an approach for the estimation of the number of equivalent axle applications a pavement section has received when loadometer data are not available.

2. Equations were determined to predict the present serviceability of highway pavements in Indiana. These equations are based on the AASHO P-equations developed at Ottawa, Illinois.

3. A method was formulated for comparing alternate pavement designs in terms of both performance and cost. This method extends the AASHO Interim Guides for Design by including a wider range of terminal serviceabilities and a measure of the total performance displayed by a highway pavement throughout its service life.

The AASHO P-equations are functions of the number and weight of axle applications, W. Therefore, if these equations are

used to predict the present serviceability of a pavement section, some means of estimating W must be available.

Axle Applications

The number of equivalent axle applications that each section received prior to rating was estimated from the traffic volume and an equivalence coefficient. The modification of the number of axle applications by means of a regional factor is discussed on page 80, in the section entitled "Flexible and Overlay Pavements."

The equivalence coefficient was determined from weighted equivalence factors which are based on equivalence traffic theory and loadometer data. Equivalence traffic theory converts all loads to 18-kip single axle equivalent loads by means of equivalence factors. Several references have stated that the use of an 18-kip single axle load as a standard is purely arbitrary. (5, 8, 9) However, this choice has several advantages.

1. The greatest legal loads in Indiana and in most states are 18-kip single and 32-kip tandem axle loads.
2. The destructive capability of a tandem axle is much less than that of a single axle of the same weight. In fact, an 18-kip single axle is approximately equivalent to a 33-kip tandem axle on flexible pavements or to a 29-kip tandem axle on rigid pavements.
3. Only the very heavy axle loads have an appreciable effect on pavement serviceability, because of the logarithmic nature of the relationship between equivalence factors and axle loads, as shown in Figure 1.

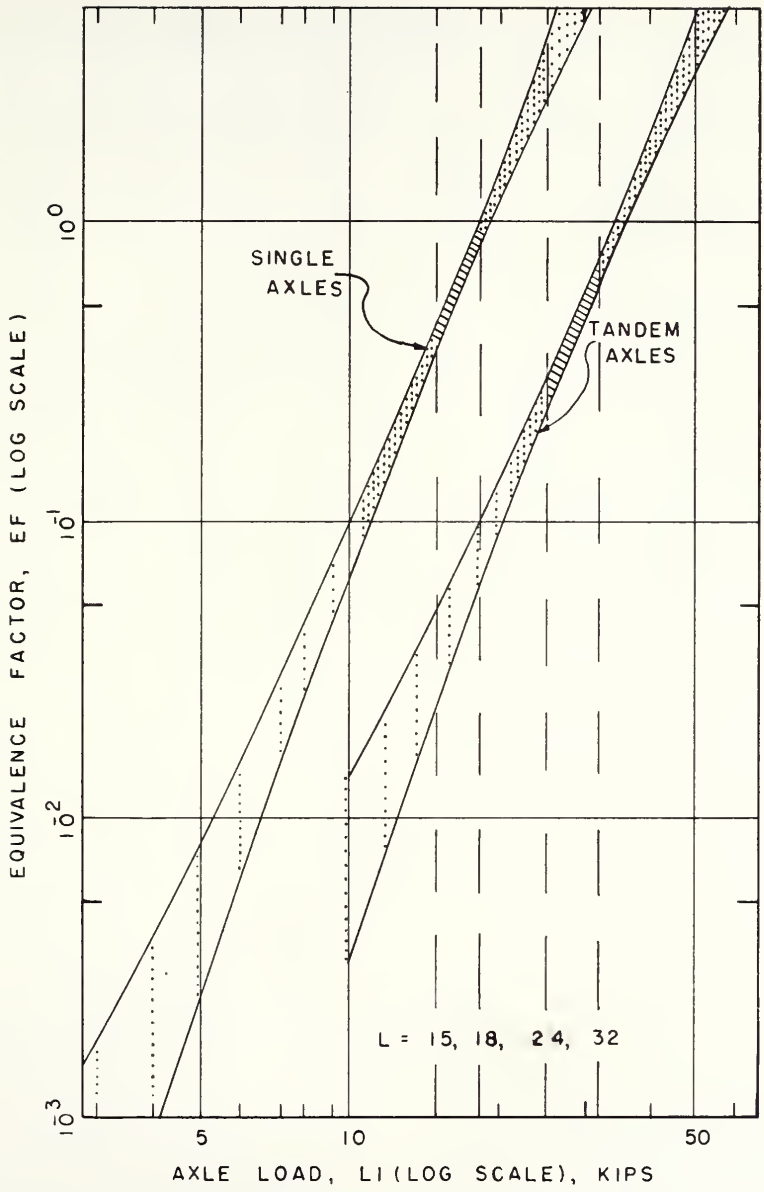

FIGURE I. GENERAL SHAPE OF EQUIVALENCE FACTOR VERSUS AXLE LOAD

4. As further illustrated in this figure, the spread in equivalence factors due to the influence of pavement thickness and terminal serviceability is at a minimum in the critical ranges of 15 to 18 kips for single axles and 24 to 32 kips for tandem axles. The utilization of this minimum spread is especially important when equivalence factors are estimated on the basis of axle load and type only.

The use of a standard at the high end of the scale is necessitated by the inherent error in equivalence traffic theory itself. An equivalence factor is computed as the ratio between the effects of two homogeneous traffic streams. It is a broad assumption that this ratio can be used to predict the destructive effect of a heterogeneous traffic stream. Hence to be on the safe side, the values of Rho, Beta, and W are based on the most significant elements of the heterogeneous traffic stream, and the most significant equivalence factors are those near one, where the error due to mixed traffic should be the least.

The equivalence factors for various axle loads are listed in the AASHO Interim Guides for Design for both single and tandem axles, at terminal serviceabilities of 2.0 and 2.5, for effective thicknesses of rigid pavements equal to 6, 7, 8, 9, 10, and 11 in., and for effective thicknesses of flexible and overlay pavements equal to 1, 2, 3, 4, 5, and 6 in. (1, 2) For the purpose of this investigation, equivalence factors were also determined for axle loads from 2 to 48 kips

for terminal serviceabilities of 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0, and for the same thicknesses as specified in the AASHO Interim Guides for Design. A sample listing of these equivalence factors is given in Tables 4 and 5.

Inspection of all the equivalence factors computed led to the conclusion that variations in the thickness and terminal serviceability of the pavement had relatively little effect on the equivalence values. For each pavement and axle type, a linear regression analysis was run between equivalence factors and axle load only. The results of this study are shown in Table 6. The high correlation coefficients and the low standard errors of estimate demonstrate that the influence of terminal serviceability and effective thickness can be neglected without any significant loss in precision. Thus, for all practical purposes, equivalence factors are simply functions of axle type and axle load.

Weighted Equivalence Factors

The use of equivalence factors permits the solution of the AASHO P-equations directly when the individual vehicle axle weights are known. However, the axle-load distributions were not available for the sections included in this study. Therefore, some means of estimating the effect of traffic from known parameters was necessary for each study section.

To eliminate the need for obtaining the distribution of vehicles by axle load for each pavement section, the weighted

Table 4. Equivalence Factors for 6-Kip Single Axle Loads on Rigid Pavements

Effective Thickness, D (in.)	Terminal Serviceability Level, Pt					
	1.5	2.0	2.5	3.0	3.5	4.0
7	0.0099	0.0104	0.0111	0.0119	0.0133	0.0160
9	0.0099	0.0100	0.0101	0.0103	0.0105	0.0109
11	0.0099	0.0099	0.0100	0.0100	0.0100	0.0101

Table 5. Equivalence Factors for 14-Kip Single Axle Loads on Rigid Pavements

Effective Thickness, D (in.)	Terminal Serviceability Level, Pt					
	1.5	2.0	2.5	3.0	3.5	4.0
7	0.3355	0.3462	0.3598	0.3782	0.4056	0.4572
9	0.3355	0.3378	0.3406	0.3442	0.3494	0.3355
11	0.3355	0.3360	0.3366	0.3375	0.3386	0.3406

Table 6. Equations for Equivalence Factor as a Function of Axle Load and Axle Type Only

Pavement Type	Axle Type	Equation for Equivalence Factor, EFi	Standard Error of Estimate	Correlation Coefficient
Rigid	Single	$EFi = 1.80 \times 10^{-6} (L1 + L2)^{4.46}$	0.04	0.993*
Rigid	Tandem	$EFi = 1.74 \times 10^{-7} (L1 + L2)^{4.53}$	0.03	0.998*
Flexible	Single	$EFi = 6.64 \times 10^{-6} (L1 + L2)^{4.03}$	0.11	0.948*
Flexible	Tandem	$EFi = 1.82 \times 10^{-7} (L1 + L2)^{4.42}$	0.18	0.826*
Combined	Single	$EFi = 3.45 \times 10^{-6} (L1 + L2)^{4.25}$	0.09	0.970*
Combined	Tandem	$EFi = 1.77 \times 10^{-7} (L1 + L2)^{4.48}$	0.17	0.921*

* Significant at the 1 percent level.

equivalence factor approach was devised in this pavement performance evaluation. The weighted equivalence factor is the average equivalence factor for the entire traffic stream. The total number of equivalent 18-kip single axle applications, W, is approximated by the product of the weighted equivalence factor and the total number of vehicle applications of all types.

$$W = (WEF)(V)$$

$$W = (WEF)(ADT)(Y)(365 \text{ days/year})$$

where:

W = the cumulative number of equivalent 18-kip single axle applications,

WEF = the weighted equivalence factor,

V = the actual number of vehicles,

ADT = the average daily traffic in one direction, and

Y = the number of years from the time of construction of the section to the time the present serviceability is to be estimated.

The weighted equivalence factor approach involves three distinct phases:

1. Determination of the possibility of computing from loadometer data a single value which fulfills the definition stated above.

2. Development of equations which estimate the WEF from truck count data.

3. Discovery of an adequate approximation of the WEF, called the equivalence coefficient, for the highway type.

Each of these results was achieved with the use of data from the Indiana State Highway Commission loadometer stations.

The weighted equivalence factor is defined as the summation over all axles of the equivalence factor for each axle, divided by the total traffic volume counted in a 24-hour period. Because only a sample of the vehicles counted at a loadometer station is weighed, the weighted equivalence factor was determined in the following manner.

1. The equivalence factors for the trucks actually weighed were first computed. The sum of these values, divided by the number of trucks weighed, yielded the average equivalence factor per weighed truck.

2. It was assumed that the average equivalence factor could be applied to all of the trucks in the traffic stream. Thus, the average factor was multiplied times the number of trucks counted at the weigh station to give the total equivalence factor for the traffic distribution.

3. The weighted equivalence factor was expressed as a ratio of the total factor to the total traffic (all vehicles). Therefore, the total number of equivalent 18-kip axle loads could be determined by multiplying the weighted equivalence factor times the ADT.

All axles, even truck steering axles, were considered in the determination of the weighted equivalence factors. Steering axles were ignored in the derivation of the AASHO

P-equations at the Road Test, because the steering axles of the test trucks had such a small effect on the behavior of the AASHO test pavements compared to the rear axles that they could be neglected with little loss in precision. However, truck steering axles have such a great effect on the performance of highways compared to car axles that they were included in this study of Indiana pavements.

Weighted equivalence factors were computed with the traffic composition and weight data from the 22 loadometer stations for each of the three years, 1963, 1964, and 1965. For each distribution 48 separate WEF's were computed. The sets of equivalence factors used to compute the weighted equivalence factors were based on all combinations of the following variables: two types of pavement, rigid and flexible (overlay pavement is included in the flexible category); six levels of terminal serviceability, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0; and four effective thicknesses. The effective thicknesses for rigid pavements were 7, 9, 11 in. and an "average" value. The arthmetic mean of the equivalence factors for 7, 8, 9, 10, 11, and 12 in. was selected as the equivalence factor for the "average" value. The effective thicknesses for flexible pavements were 2, 4, and 6 in. and an "average" value based on EF's for 1, 2, 3, 4, 5, and 6 in.

From the evaluation of this data, the following trends were observed in the weighted equivalence factors.

1. There is a large amount of variation in the WEF's among loadometer stations.

2. For a given station, the amount of variation is slight among the WEF's for the three years.

3. The weighted equivalence factor is higher for rigid pavements than for flexible pavements, if the terminal serviceability is less than 3.5; otherwise, the reverse is true.

4. When the serviceability is less than 3.5, for all practical purposes the WEF is not dependent on thickness and terminal serviceability.

R. H. Larson computed, as a prelude to his study of the ISHC loadometer station data, the average axle weight for each of 12 truck types at the 20 stations operated in 1963. The possibility of estimating the weighted equivalence factor for each station by using these average axle weights was investigated.

The WEF calculated from an average axle load for each truck type was considerably lower than the WEF calculated from the actual load on each axle weighed at a given loadometer station. This discrepancy is explained by the logarithmic manner in which equivalence factors vary with load. The use of an average axle weight for each truck type to calculate weighted equivalence factors is not recommended.

Examination of the 48 weighted equivalence factors for each traffic composition and weight distribution indicated that the WEF determined from an average terminal serviceability level and an "average" thickness was a good estimate of the entire set of weighted equivalence factors for that

distribution. The WEF's are presented in Table 7 for the traffic composition and weight distributions determined from the Indiana State Highway Commission loadometer station data.

Equivalence Coefficients

The purpose of quantifying the weighted equivalence factors was to find some means of characterizing the traffic composition and weight distribution on each of the 160 pavement study sections, because loadometer data were not available. As a second step in determining w, a multiple linear regression analysis was performed to reveal the relationship between the traffic parameters and the weighted equivalence factors for the 61 traffic distributions.

Multiple unit trucks, all trucks, and trucks excluding ISHC truck types 11 and 12, each of these measures expressed as a percentage of the total daily traffic, correlated well with the WEF as can be seen from Table 7. Truck types 11 and 12, abbreviated to truck type 1 in the tables, are panels, pickups, and other light trucks. The more important results of the regression analysis are summarized in Table 8.

Indiana highways tend to fall into three separate classes by traffic weight distribution. The percentages of trucks on highways of the same class are approximately constant. The three classes of truck route are:

1. Class I Truck Routes = all Interstate routes and US-numbered routes connecting major population centers.
2. Class II Truck Routes = all other primary state

Table 7. Weighted Equivalence Factors, WEF, for the 22 Loadometer Stations - 1963, 1964, 1965

Station & Year	Average Daily Traffic	Percent Trucks Except Type 1	Percent Trucks	WEF Rigid Pavements	WEF Flexible & Overlay Pavements
5 63	5900	38.6	44.1	0.39	0.28
64	5900	40.1	44.3	0.41	0.29
65	5700	38.1	42.6	0.39	0.28
14 63	9100	32.3	37.2	0.31	0.22
64	10000	34.0	38.6	0.37	0.25
65	10300	34.7	38.7	0.34	0.23
2 63	3700	30.2	35.6	0.20	0.14
64	4400	28.6	34.7	0.23	0.16
65	4300	30.0	36.6	0.24	0.17
16 63	5400	26.6	28.3	0.20	0.14
64	5800	26.8	32.3	0.23	0.16
65	5400	24.6	32.4	0.18	0.12
42 63	8300	26.4	31.1	-	-
64	8300	29.2	33.9	0.25	0.18
65	8800	26.3	31.7	0.23	0.16
27 63	5300	24.7	29.6	0.21	0.15
64	5100	26.7	32.3	0.26	0.18
65	5000	24.8	31.4	0.18	0.13
23 63	2700	22.7	31.3	0.13	0.10
64	3500	24.3	33.5	0.16	0.12
65	3600	26.7	35.8	0.15	0.11
68 63	8200	22.3	30.5	0.20	0.14
64	8000	19.3	28.4	0.12	0.10
65	8300	20.3	29.4	0.14	0.10
12 63	8700	21.6	28.2	0.16	0.11
64	8700	21.8	28.3	0.16	0.12
65	4000	18.8	25.9	0.14	0.10
81 63	3000	20.2	27.2	0.14	0.11
64	3900	23.5	30.8	0.18	0.14
65	3600	17.6	28.5	0.14	0.10
15 63	11300	19.2	23.4	0.15	0.11
64	12300	20.5	24.8	0.15	0.11
65	11500	18.8	24.1	0.12	0.09

Table 7. (cont'd.)

Station & Year	Average Daily Traffic	Percent Trucks Except Type 1	Percent Trucks	WEF Rigid Pavements	WEF Flexible & Overlay Pavements
45B 63	5900	18.4	26.1	0.12	0.08
64	6100	15.3	22.8	0.07	0.05
65	6000	13.8	23.6	0.07	0.05
63 63	14500	16.2	20.8	0.13	0.09
64	12700	11.0	16.3	0.07	0.09
65	12600	11.2	17.6	[illegible]	0.05
4 63	5100	16.2	23.9	0.10	0.07
64	8600	13.6	20.3	[illegible]	0.09
65	[illegible]	18.7	15.3	[illegible]	[illegible]
1 63	2700	13.5	25.3	[illegible]	.07
64	4300	12.0	35.3	-	-
65	2900	11.3	20.9	-	-
3 63	6600	16.7	[illegible]	0.08	[illegible]
64	6900	14.7	23.6	0.05	.04
65	6800	13.3	22.4	0.05	0.04
83 63	10100	14.8	21.2	0.11	0.08
64	10100	17.9	24.7	0.13	0.09
65	11700	16.0	24.4	0.12	0.08
58B 63	18500	14.6	20.4	0.11	0.08
64	19700	15.0	21.2	0.11	0.08
65	22400	14.4	21.3	0.11	0.08
33 63	10700	10.9	18.1	0.08	0.06
64	10700	11.2	19.1	0.10	0.07
65	10900	10.1	19.2	0.07	0.05
75 63	12000	10.4	18.3	0.10	0.07
64	12000	11.4	18.3	0.08	0.05
65	12900	11.9	20.6	0.08	0.06
29 63	-	-	-	-	-
64	4300	16.6	21.3	0.05	0.04
65	4600	9.9	20.6	0.06	0.04
34 63	-	-	-	-	-
64	5700	3.0	10.7	0.01	0.01
65	4600	3.5	12.0	0.01	0.01

Table 8. Estimate of Weighted Equivalence Factor, WEF, by Traffic Composition

Variables	Equations	Standard Error of Estimate	Correlation Coefficient
	For Rigid Pavements		
Percent Multiple Unit Trucks, % MU	WEF = -0.0076 + 0.0108 (% MU)	0.028	0.957 *
Percents Multiple Unit and Single Unit Trucks, % MU and % SU	WEF = 0.0128 - 0.0015 (% SU) + 0.0107 (% MU)	0.028	0.957 *
Percent Trucks Except Type 1, % TRKX1	WEF = -0.0509 + 0.1010 (% TRKX1)	0.033	0.940 *
Percent Trucks, % TRK	WEF = -0.1280 + 0.0103 (% TRK)	0.043	0.890 *
	For Flexible & Overlay Pavements		
Percent Multiple Unit Trucks, % MU	WEF = -0.0023 + 0.0075 (% MU)	0.019	0.959 *
Percent Trucks Except Type 1, % TRKX1	WEF = -0.0333 + 0.0071 (% TRKX1)	0.021	0.947 *
Percent Trucks, % TRK	WEF = -0.0878 + 0.0072 (% TRK)	0.029	0.898 *

* Significant at the 1 percent level.

highways.

3. Class III Truck Routes = all secondary state highways.

All highway in a given class have similar weighted equivalence factors.

The third step in determining the number of equivalent axle applications for each study section was the development of equivalence coefficients for each class of truck route. An equivalence coefficient, F, is the average of the weighted equivalence factors for highways of a given class as determined from both loadometer and truck count data. The F for each type of pavement and class of truck route is listed in Table 9.

The equivalence coefficient, F, was used to determine the number of 18-kip equivalent axle applications which each study section received. The equivalence coefficient was substituted for the weighted equivalence factor in the equation for equivalent axle applications.

$$W = (F)(V)$$

$$W = (F)(ADT)(V)(365 \text{ days/year})$$

where:

W = the cumulative number of equivalent 18-kip single axle applications,

F = the equivalence coefficient,

V = the number of vehicles,

ADT = the average daily traffic in one direction, and

Y = the number of years from the time of construction to the time the present serviceability is to be estimated.

Table 9. Equivalence Coefficient, F, for the Three Classes of Truck Routes

Class of Truck Route	Rigid Pavement	Flexible & Overlay Pavements
I	[illegible]	[illegible]
II	[illegible]	[illegible]
III	[illegible]	[illegible]

In the absence of loadometer or truck count data, the equivalence coefficient is the best estimate of the weighted equivalence factor. The equivalence coefficient is a reliable and simple method for determining the number of 18-kip equivalent axle applications that a pavement receives over a specified interval of time.

Indiana Serviceability Equations

Three sets of equations for predicting the present serviceability of highway pavements in Indiana were developed with the AASHO rigid and flexible P-equations as a basis. One set of equations is applicable for each type of pavement, that is, rigid, flexible, and overlay.

Rigid Pavements

The AASHO rigid P-equation was used to predict the present serviceability of the 80 concrete pavement sections included in this study. With no modifications, this equation estimated the present serviceability of each of these sections within ± 1.6 of the actual PSR at the 5-percent level of significance.

A modified equation, termed the Indiana rigid serviceability equation, was then determined from a regression analysis performed between the predicted and actual present serviceability values. This modified equation is:

$$P_{Ind} = 4.0 - 2.5 \, (W / \varrho_{18})^{\beta_{18}}$$

where:

P_{Ind} = the present serviceability for a given Indiana rigid pavement as estimated by the number of axle applications in mixed traffic.

W = the number of equivalent 18-kip single axle applications, and

ρ_{18} and β_{18} are the values of the AASHO equations for Rho and Beta, respectively, when L1 = 18.0 kips, L2 = 1.0, and D = the effective thickness of the section under consideration.

Rho18 and Beta18 can be estimated from Figures 11 and 12 in Appendix A. The number of equivalent axle applications is estimated from an equivalence coefficient and the ADT of the highway section.

The Indiana rigid serviceability equation estimated the present serviceability of each of the study sections within $\pm$1.1 of the actual PSR at the 5-percent level of significance. The use of this equation rather than the AASHO equation reduced the standard error of estimate by 28.3 percent. A comparison of the AASHO and Indiana equations is shown in Table 10.

The need for the modification of the AASHO rigid P-equation is due in part to the fact that the average initial serviceability of Indiana rigid pavements is lower than the average initial serviceability of the AASHO Road Test pavement sections. The average initial serviceability of 17 new rigid Indiana pavements tested by F. M. Holloway in 1955 was 4.1 with a standard deviation of 0.3. (10) A study of 13 new concrete pavements conducted in 1966 by the personnel of the Indiana State Highway Commission Research and Training

Table 10. Comparison of the AASHO and Indiana Rigid Serviceability Equations

Equation	Variance, S_E^2	Standard Error of Estimate, S_E	Correlation Index, r^2	Correlation Coefficient, r
AASHO Rigid P-Equation, $P = 4.5 - 3.0\ (W / \rho)^{\beta}$				
Road Test Data	0.058	0.240	0.160	0.400 *
Indiana Data	0.492	0.705	0.330	0.575 *
Indiana Rigid Serviceability Equation, $P_{Ind} = 4.0 - 2.5\ (W / \rho)^{\beta}$				
Indiana Data	0.256	0.506	0.490	0.700 *

* Significant at the 5 percent level.

Center determined a mean serviceability of 4.0 with a standard deviation of 0.2. These data substantiate the fact that the average initial serviceability of new portland cement concrete pavements in Indiana is approximately 4.0.

No modification was deemed necessary to account for the different soil types occuring as subgrades under the rigid pavement sections because the performance of concrete pavements is influence to only a slight degree by the subgrade if a subbase is provided. (2, 4) In Indiana prior to the mid-1940's, concrete pavements were constructed without subbases and without air-entrained concrete. Ten pre-1945 pavements were included in this study. Six of these pavements had an actual serviceability that was considerably lower than the predicted value. Because all rigid pavements now built in Indiana have both a subbase and air-entrainment, the variation in subgrades and lack of air-entrainment does not need to be considered in the rigid serviceability equation.

The Indiana rigid equation is applicable for determining the present serviceability of portland cement concrete pavements constructed in Indiana according to the Indiana State Highway Commission Standard Specifications. Both plain and reinforced pavements were studied. However, the majority of the pavement sections included in this study were reinforced. In the case of dual-lane highways, this equation is to be used for the driving lane only, because

this is the controlling lane for pavement design. All serviceability ratings and roughometer measurements are made in the right-hand lane.

Regression equations for P_{Ind} were also obtained by assuming 4- and 8-percent annual growth rates of traffic. These equations are the same as the equation chosen, shown in Table 10, which is based on a traffic growth rate of 6-percent per year.

Flexible and Overlay Pavements

Both the AASHO weighted and unweighted flexible P-equations with the soil support factors obtained from this study were used to predict the present serviceability of the flexible and overlay study sections. The AASHO weighted equation was developed at the Road Test by weighting the data used to compute Rho and Beta for the unweighted equation by a seasonal weighting factor. These equations predicted the present serviceability of each of the flexible and overlay pavements considered in this study within ± 2.0 of the actual present serviceability at the 5-percent level of significance.

The Indiana flexible and overlay serviceability equations were obtained from a regression analysis between the serviceability predicted by the AASHO flexible P-equations and the present serviceability determined by a 30-member rating panel. The weighted serviceability equations which were determined for conditions in Indiana are as follows:

flexible pavements,

$$P_{Ind} = 3.5 - 2.0 (W / \varrho_{18})^{\beta 18}$$

overlay pavements,

$$P_{Ind} = 4.0 - 2.5 (W / \varrho_{18})^{\beta 18}$$

where:

P_{Ind} = the present serviceability for a given Indiana flexible or overlay pavement as estimated by the number of axle applications in mixed traffic.

W = the number of equivalent 18-kip single axle applications, and

ϱ_{18} and β_{18} = the values of the AASHO weighted equations for Rho and Beta, respectively, when L1 = 18.0 kips, L2 = 1.0, and SN = the effective thickness of the section under consideration as modified by the soil support factor, S, determined from the soil parent material map.

Rho18 and Beta18 can be estimated from Figures 13 and 14 in Appendix A.

The weighted flexible and overlay serviceability equations predicted the present serviceability of the study sections within $\pm$1.1 and $\pm$1.6, respectively, of the actual PSR at the 5-percent level of significance. A comparision between the AASHO flexible P-equations and the Indiana flexible and overlay serviceability equations is given in Table 11.

The regression analysis yielded the same Indiana serviceability equations whether the weighted or the unweighted values for Rho18 and Beta18 were used. This similarity occurs because the present serviceability ratings of very few of the flexible and overlay study sections were

Table 11. Comparison of the AASHO and Indiana Flexible and Overlay Serviceability Equations

Serviceability Equation	S_E^2	S_E	r^2	r
AASHO Flexible P-Equation, $P = 4.2 - 2.7 (W / \rho)^{\beta}$				
Road Test Data				
Weighted Equation	0.22	0.47	0.70	0.84*
Unweighted Equation	0.29	0.54	0.48	0.69*
Indiana Data				
Weighted Equation	0.79	0.89	0.05	0.22#
Unweighted Equation	0.80	0.89	0.06	0.25*
Indiana Flexible Serviceability Equation, $P_{Ind} = 3.5 - 2.0 (W / \rho)^{\beta}$				
Indiana Data				
Weighted Equation	0.27	0.52	0.13	0.36*
Unweighted Equation	0.27	0.52	0.16	0.40*
Indiana Overlay Serviceability Equation, $P_{Ind} = 4.0 - 2.5 (W / \rho)^{\beta}$				
Indiana Data				
Weighted Equation	0.55	0.74	0.07	0.26#
Unweighted Equation	0.55	0.74	0.08	0.29#

* Significant at the 5 percent level.
\# Significant at the 10 percent level.

below 2.0. It is believed that over the full range of serviceability levels, the weighted equations are more precise for Indiana conditions. However, the use of a regional factor of 1.2 with the weighted equations did not increase the correlation coefficient significantly at the 5 percent level.

The weighted and unweighted equations for Betal8 give approximately the same values as long as the SN is greater than 2.5, as shown in Table 12. However, the weighted values of Rhol8 given in the same table are approximately half the unweighted values. As a result, the weighted Indiana flexible and overlay serviceability equations predict the serviceability for a given pavement section one- or two-tenths lower than the unweighted Indiana equations do. This difference increases as W approaches Rhol8.

The Indiana flexible and overlay serviceability equations are applicable only to shoulder lanes of highways built according to the Indiana State Highway Commission Standard Specifications. Neither these equations nor the AASHO P-equations are valid for bituminous pavements having effective thicknesses which are less than 1.5 in.

This restriction applies to pavements of the ISHC type 4231. All sections of the flexible and overlay classifications were eliminated from this investigation if their effective thicknesses were less than 1.5 in.

There are two reasons why these equations can not be used to determine the present serviceability of a pavement whose effective thickness is less than 1.5 in. The first

Table 12. RHO, ρ, and BETA, β, as Functions of Effective Thickness for Flexible Pavements

Effective Thickness SN	Weighted		Unweighted		Ratios	
	ρ_{18w}	β_{18w}	ρ_{18}	β_{18}	ρ_{18} / ρ_{18w}	β_{18} / β_{18w}
1.5	3.38 E3*	9.81	8.17 E3	47.45	2.42	4.83
2.0	1.86 E4	4.05	4.17 E4	9.98	2.25	2.47
2.5	7.89 E4	2.04	1.65 E5	2.89	2.09	1.42
3.0	2.75 E5	1.22	5.46 E5	1.18	1.99	0.97
3.5	8.30 E5	0.85	1.56 E6	0.68	1.88	0.80
4.0	2.22 E6	0.66	4.01 E6	0.51	1.81	0.77
4.5	5.43 E6	0.56	9.40 E6	0.45	1.73	0.80
5.0	1.23 E7	0.50	2.05 E7	0.42	1.67	0.84
5.5	2.59 E7	0.47	4.19 E7	0.41	1.61	0.87
6.0	5.19 E7	0.45	8.12 E7	0.41	1.56	0.91
6.5	9.89 E7	0.43	1.50 E8	0.40	1.52	0.93
7.0	1.81 E8	0.42	2.68 E8	0.40	1.48	0.95
7.5	3.19 E8	0.42	4.61 E8	0.40	1.45	0.95

* 3.38 E3 = 3.38×10^3

reason is that equivalence traffic theory does not give accurate results for low effective thicknesses. (18) Secondly, the strength coefficients available from the AASHO Road Test are the average values for all the flexible sections. These values do not apply to thin pavements carrying light traffic. (4)

The effective thickness of each pavement study section was computed from the Road Test strength coefficients for its construction materials. The strength coefficients for the pavement types included in this analysis are given in Table 17 on page105. These coefficients strictly apply only when the weighted AASHO flexible equation is employed. For the unweighted equations, the strength coefficients for the surface and the subbase are approximately 90 percent of the values listed in Table 17. The coefficients for the base course are the same for both equations. These variations in coefficient values have only a slight influence on the effective thickness of a given pavement. Therefore, the weighted strength coefficients were used to determine effective thicknesses for use with both the weighted and unweighted serviceability equations.

Regression equations for P_{Ind} were also obtained in both the flexible and overlay analyses by assuming 4- and 8-percent annual growth rates of traffic. These equations are the same as the equations shown in Table 11, which are based on a traffic growth of 6 percent per year.

An attempt was made to use the AASHO flexible P-equations with no modification to effective thickness for subgrade soil support. Analyses were also performed using constant soil support values of 4.5 and 4.8 for all sections. The lack of correlation and high standard errors of estimate demonstrate that the relative subgrade support for each section must be included as a variable in the Indiana equations.

AASHO Soil Support Scale. Soil variability was not included in the factorial analysis at the AASHO Road Test. Rather, the objectives of the Road Test required:

> that the test pavements be built on a uniform embankment with the top 3 ft constructed of a soil meeting the AASHO A-6 Classification and having a Group Index of 9 to 13, inclusive. Borings made in three areas near the project revealed that sufficient quantities of suitable soil were available to meet the requirement. (3)

The AASHO P-equations are strictly applicable only to pavements built on subgrade soils having similar characteristics to the soil type under the test pavements at the Road Test.

In order to extend the applicability of their Design Charts 400-1 and 400-2 (nomographs whose general shape is shown in Figure 2), the AASHO Committee on Design developed a soil support scale modifying the AASHO flexible P-equation to account for the effects of subgrades of different strength characteristics. (5) The Committee explained on page 400 of

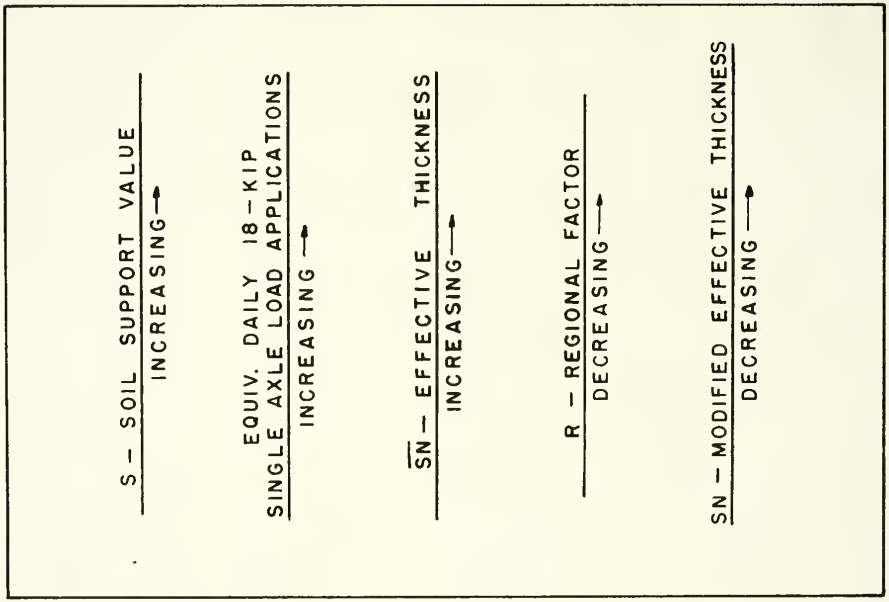

FIGURE 2. GENERAL FORMAT OF AASHO NOMOGRAPHS FOR FLEXIBLE AND OVERLAY PAVEMENT DESIGN SOURCE - REF. (1)

HRB Special Report 73 how they arrived at the soil support scale:

> Only one point is obtained on the soil support scale in plotting the design charts. It represents the support value of the roadbed soils used on the Road Test and has been given a value of 3.0. A second point on the scale was established by studying the performance of sections on Loop 4 that had the greatest thickness of crushed stone base course. It was assumed that the influence of the roadbed soils would be minimized, and that the base course would, to a large degree, determine the performance of the section. The studies indicate that about 4.5 in. of asphaltic plantmix surfacing on a soil having the support characteristics of the crushed stone would carry approximately 7,300,000 single-axle load applications to a terminal serviceability index of 2.0. Accordingly, a second point on the soils support scale is established by projecting a line from 1.98 (4.5 x 0.44)* on the center SN-scale through 1,000 (7,300,000 / 20 x 365)** on the 18 kip load scale to an intersection with the soil support scale. This new point has been given a value of 10.0. A linear scale between 3.0 and 10.0 has been assumed and is extended to zero. (5)

The necessity of including a soil support factor in the study of flexible pavement performance is obvious. However, the AASHO Design Committee failed to point out the assumptions that were necessary to arrive at their soil support scale.

First, the flexible sections of Loop 4 consisted of 3, 4, and 5 in. of asphaltic plantmix surfacing on 0, 3, and 6 in. of crushed stone base, placed on 4, 8, and 12 in. of sand gravel subbase. The 4.5 in. of surface assumed in

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* SN = (A1)(D1), where A1 = 0.44, and D1 = 4.5 in.

** 1,000 equivalent 18-kip single axle applications/day = (7,300,000 applications) / (20 years x 365 days/year).

determining the AASHO soil support scale is an interpolation.

Secondly, the maximum number of axle load applications that any section in the test received was 1,114,000. Therefore the 7,300,000 axle load applications to a terminal serviceability of 2.0 is a gross extrapolation.

Furthermore, although the AASHO Design Committee did not elaborate on the "study of the performance of Loop 4," it is the opinion of this researcher that their analysis was similar to the one that follows. Lane 1 of Loop 4 was used because the test traffic consisted of 18-kip single axle vehicles, and therefore the use of equivalence factors was unnecessary. At the conclusion of the test, the three sections in Lane 1 of Loop 4 having the greatest thickness of base, 6 in., and subbase, 12 in., still had a serviceability greater than 1.5. The design of these sections and their serviceabilities at the beginning and end of the test are given in Table 13.

The serviceability trends for these three sections can be plotted from the 6 points (W,P) given in the table. The log of serviceability, P, plotted against the log of axle applications, W, yields a straight line. (5) This graph is reproduced in Figure 3.

The number of axle applications necessary to reach a P of 2.0 was probably determined from a similar graph by the AASHO Committee on Design in their analysis. For the 3-in. surface, test section 621, W is 47,000; for the 4-in. surface, test section 593, W is 500,000; while for the

Table 13. The Characteristics of the Non-Failing Sections of Loop 4 at the AASHO Road Test

Test Section Number	621	593	581
Loop Number	4	4	4
Lane Number	1	1	1
Axle Load (kips)	18	18	18
Axle Type	Single	Single	Single
Surface (inches)	3	4	5
Base (inches)	6	6	6
Subbase (inches)	12	12	12
P at W = 0	4.2	4.2	4.2
P at W = 1,114,000	1.6	1.9	3.3

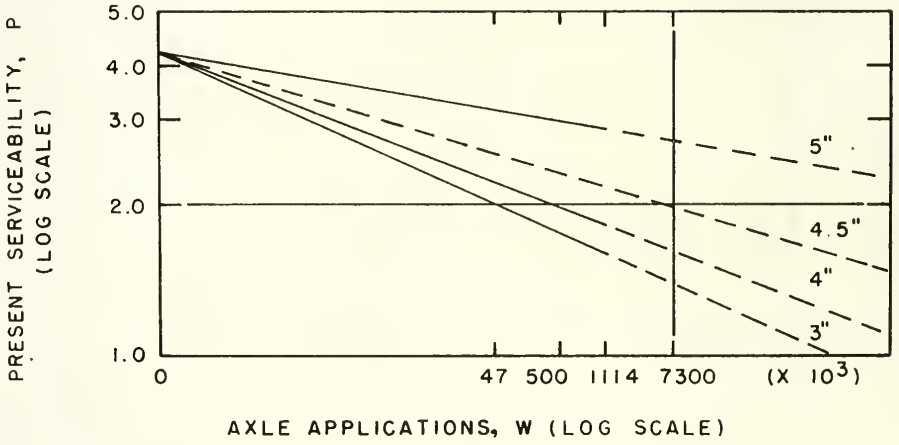

FIGURE 3. PRESENT SERVICEABILITY VERSUS NUMBER OF 18-KIP SINGLE AXLE APPLICATIONS FOR LOOP 4 AT THE AASHO ROAD TEST

5-in. surface, test section 581, W is over 6 x 10^{19} when P = 2.0. The serviceability trend is interpolated on the graph for a pavement section of similar characteristics, but having 4.5 in. of surface. The 4.5-in. trend intersects the terminal serviceability level of 2.0 at 7,300,000 18-kip axle load applications. The soil support scale was established from this point.

However, it would appear that the reasoning used to determine the soil support scale would remain just as valid if the number of axle applications associated with either the 4- or 5-in. surface were used. If the 4-in. design were used, the second point on the scale would be established by projecting a line from 1.76 (SN = 0.44 x 4.0) on the center SN-scale through 68.5 (applications/day = 500,000 / (20 x 365)) on the 18-kip load scale to an intersection with the soil support scale. If this were done, a scale of approximately three-quarters of the height of the present soil support scale would result. If a similar procedure were undertaken with the 5-in. design, a scale of about 5 times the size of the scale established would be necessary. Unless the AASHO Committee had some other information, it appears that the use of the 4.5-in. interpolation not only was arbitrary, but that it influenced immensely the soil support scale that was established.

It is further stated by the AASHO Design Committee in HRB Special Report 73:

> The reasonableness of the soil support scale has been established by correlation with a number of other design procedures used in the United States. It has been found that the correlation varies with the soils test procedure used and the manner in which the test is run. Particularly important is the compaction procedure used in preparing the test specimens. Further research in the satellite test program will be required to establish fully the validity of the soils support scale. Typical correlation curves between commonly used soils test procedures and the soil support value are given. (5)

These correlations have been obtained by testing samples of the crushed stone base and the subgrade soil and comparing these results to the soil support values which have been arbitrarily assigned: 10.0 for the base and 3.0 for the subgrade. As far as this researcher can determine this was the entire correlation procedure. A suitable scale (logarithmic or arithmetic) was assumed for the intermediate values, depending on the test procedure being correlated.

Although the reasonableness of the soil support scale may have been established, the degree of its accuracy is still open to question. Unfortunately, the fact remains that the subgrade influences the performance of flexible pavements.

The use of U.S. Department of Agriculture County Soil Surveys as a means of estimating the value of the subgrade soil support for each section was investigated. This method was unsuccessful because of the nature of the data provided in these surveys and the limitations of the AASHO soil support correlation.

Furthermore, the large number of different soil series, typically from 10 to 30 or more, under each section made this method tedious and unprofitable. Its use was discontinued after the soil support values had been estimated for 24 percent of the sections for which soil surveys were available. The values that were obtained indicate that a typical soil support value for Indiana is 4.8.

The Soil Rating Panel was finally selected as the most practical means of estimating the relative support provided by the subgrade of a pavement section. Ratings were obtained on a scale from 0.0 to 10.0 for each of the 18 major soil units considered. These ratings and various statistics are presented in Tables 14 and 15. The following trends may be noted.

1. Each of the panelists used almost the entire rating scale.
2. Although the first panelist was consistently above the median rating for a given soil type and the third panelist was consistently below the median, the other four members of the panel tended to vary randomly above and below the median rating.
3. The ratings for a given soil unit do vary. However, the median, mean, and mode are approximately the same number.

The mean panel rating was taken as the best estimate of the relative performance of a given soil type.

Because the panelists made their ratings independently

Table 14. Estimated Performance of Flexible Pavements Built on the Major Soil Units in Indiana

Major Soil Unit		Rater					
		1	2	3	4	5	6
1	Porous Substrata (Sands and Gravels)	10.0	9.5	5.5	8.5	8.5	9.0
2a	Water-Laid Sands (Except Kankakee)	9.0	7.0	4.5	8.0	7.8	8.0
2b	Kankakee Sands	10.0	4.0	3.5	5.0	7.5	7.0
3	Lakebeds	3.0	3.0	3.5	2.5	4.0	2.0
4	Recent Alluvium	9.5	4.0	3.5	0.1	3.0	4.0
5	Young Drift Till Plains (Silty-Clays)	7.0	5.0	4.5	4.0	4.7	3.0
6	Moraines	6.0	4.0	5.5	6.0	3.5	4.0
7	Ice-Laid Sand, Gravel, & Till	6.0	7.0	5.5	7.5	7.0	7.0
8	Eskers	10.0	9.5	7.5	9.0	8.4	6.0
9	Old Drift Silts and Silty-Clay	5.9	5.0	3.5	3.5	5.5	6.0
10	Wind-Deposited Sand	9.0	7.0	4.5	7.5	7.2	7.0
11	Loess - Silt	8.0	4.0	3.5	5.5	6.3	6.0
12	Limestone	6.0	3.0	4.5	5.0	5.8	6.0
13	Interbedded Limestone & Shale	6.0	4.0	3.5	4.5	4.9	3.0
14	Limestone, Sandstone, & Shale	6.0	6.0	3.5	4.5	5.1	5.0
15	Sandstone and Some Shale	7.0	5.0	4.5	6.0	6.0	6.0
16	Interbedded Shale & Sandstone	6.0	4.0	2.5	4.0	5.3	5.0
17	Muck, Peat, and Mucky Soils	0.5	0.0	0.5	0.5	0.0	0.0
Average for all Soil Units		7.0	5.1	4.1	4.8	5.8	5.2

Table 15. The Mean, Median, Mode, Range, and Size of the Soil Ratings and the Soil Support Factor Assigned for the Major Soil Units of Indiana

	Major Soil Unit	a	b	c	d	e	f
1	Porous Substrata (Sands and Gravels)	8.5	8.5	8.5	10.0-5.5	4.5	6.8
2a	Water-Laid Sands (Except Kankakee)	7.4	7.9	8.0	9.0-4.5	4.5	6.2
2b	Kankakee Sands	6.2	6.0	*	10.0-3.5	6.6	5.6
3	Lakebeds	3.0	3.0	3.0	4.0-2.0	2.0	4.0
4	Recent Alluvium	4.1	3.8	4.0	9.5-0.1	9.4	4.6
5	Young Drift Till Plains (Silty-Clays)	4.7	4.6	*	7.0-3.0	4.0	4.9
6	Moraines	4.8	4.8	4.0	6.0-3.5	2.5	4.9
7	Ice-Laid Sand, Gravel, and Till	6.7	7.0	7.0	7.5-5.5	2.0	5.9
8	Eskers	8.4	8.7	*	10.0-6.0	4.0	6.7
9	Old Drift Silts and Silty-Clays	4.9	5.3	3.5	6.0-3.5	2.5	5.0
10	Wind-Deposited Sand	7.0	7.1	7.0	9.0-4.5	4.5	6.0
11	Loess - Silt	5.6	5.8	*	8.0-3.5	4.5	5.3
12	Limestone	5.1	5.4	6.0	6.0-3.0	3.0	5.1
13	Interbedded Limestone and Shale	4.3	4.3	*	6.0-3.0	3.0	4.7
14	Limestone, Sandstone, and Shale	5.0	5.1	5.0	6.0-3.5	2.5	5.0
15	Sandstone and Some Shale	5.8	6.0	6.0	7.0-4.5	2.5	5.4
16	Interbedded Shale and Sandstone	4.5	4.5	4.0	6.0-2.5	3.5	4.8
17	Muck, Peat, and Mucky Soils	0.3	0.3	*	0.5-0.0	0.5	2.7

Key: a - Mean Rating, b - Median Rating, c - Mode Rating, d - Range of Ratings, e - Size of Range, f - Soil Support Factor, * - Multimodal

of the AASHO flexible P-equation, it was necessary to correlate the mean panel rating for a given major soil type with the AASHO equation. The correlation was done in two parts. First, a functional relationship was determined on the basis of selected pavement sections. Secondly, the soil support factors obtained from this relationship were used with the AASHO flexible P-equation to predict the present serviceability of all the study sections, and the results were checked statistically.

In the first part of the correlation procedure, each study section was located on the JHRP map to determine whether it was built on a subgrade restricted to just one major soil unit. There were 37 sections built on a total of 8 different units which met this condition.

The expected subgrade soil support values necessary to modify the respective effective thicknesses so these 37 pavements would behave in the manner they did were determined from the AASHO flexible P-equation. The PSR of each section in turn was substituted for P, and the equation was solved by a trial and error procedure for the modified effective thickness. From the modified effective thickness, the soil support factor was calculated by using the equation for SNmod which conforms to the design nomographs. (1)

By a numerical technique using the expected soil support values of the 8 major soil units, an equation was found relating the mean panel rating for a given soil unit with the soil support modification to the effective thickness used

with the AASHO p-equation. This relationship is:

$$S = 5.0 + 0.5 (\overline{R} - 5.0)$$

where:

S = the soil support factor for a given Indiana major soil unit, and

$\overline{R}$ = the mean relative performance rating for the same major soil unit.

Using this relationship, the soil support factors for all 18 major soil units were determined.

In the second part of the correlation, the weighted average soil support factor for the subgrade under each study section was calculated. The validity of these soil support factors for the major soil types was checked in the regression analyses for the flexible and overlay pavement sections. The use of these soil support factors instead of a constant value of either 3.0, 4.5, or 4.8 raised the correlation coefficient, r, from 0 to 0.36 and from 0 to 0.26 for the weighted Indiana flexible and overlay serviceability equations, respectively.

The Indiana serviceability equations for flexible and overlay pavements can not be divorced from the soil support factors used in the determination of these equations. These factors, which range from 2.5 to 7.5, are independent of the AASHO soil support scale and of the correlation of this scale with other test procedures. These factors are, however, designed for use with the nomograph given in Figure 7 of this report, and with the Design Charts 400-1 and 400-2 of the AASHO Interim Guide for Design of Flexible Pavement Structures.

Predicted Performance

When the performance of a particular pavement with known or estimated traffic volume and composition is quantified by means of the Indiana serviceability equations, the result is a series of values. When it is desirable to represent the entire series by a single value, the performance equation is used. This measure of performance, Pa, especially in conjunction with the length of service life, Y, and the terminal serviceability, Pt, gives an accurate picture of the performance of a pavement throughout its life. The performance equation is:

$$Pa = \frac{Pt + (A)(\beta 18)}{\beta 18 + 1.0}$$

where:

Pa = the performance or average serviceability of a given section of pavement during its service life,

Pt = the terminal level of serviceability,

$\beta 18$ = the exponent of the appropriate Indiana serviceability equation as a function of the effective thickness of the given pavement (estimated from Figures 12 and 14 in Appendix A), and

A = the value of the appropriate Indiana serviceability equation when W = 0. A equals 4.0, 3.5, and 4.0 for rigid, flexible, and overlay pavements, respectively.

The value of Pa was calculated for rigid, flexible, and overlay pavements of various effective thicknesses at several terminal levels of serviceability. The results are listed in Tables 19, 20, and 21 on page 111

The limit of Pa as Beta18 approaches 1.0 equals the

linear average of the terminal and initial serviceabilities, i.e.:

$$\underset{\beta 18 \rightarrow 1.0}{\text{Limit}} \; Pa = \underset{\beta 18 \rightarrow 1.0}{\text{Limit}} \left[\frac{Pt + (A)(\beta 18)}{\beta 18 + 1.0} \right] = \frac{Pt + A}{2.0} \; .$$

Beta18 is approximately 1.0 for effective thickness, D, greater than 10.0 inches for rigid pavements, and for SN between 3.0 and 4.0 for flexible and overlay pavements.

For a given pavement with its traffic, performance can only be increased by raising the terminal serviceability level, which is accomplished by shortening the number of years, Y, that the pavement remains in service before being resurfaced. A thinner pavement provides slightly higher performance than a thicker pavement if both have the same terminal level of serviceability. However, the increase in performance is offset by the fact that the thinner pavement reaches this serviceability level much sooner than the thicker design. Although it may seem unusual that the performance displayed by a pavement decreases as the design is improved, the necessity of this result is shown in Appendix D. Nevertheless, a pavement with a greater effective thickness will perform better than a thinner one if both are subjected to the same traffic for the same length of time.

By judicious choice of terminal serviceability and pavement design in accordance with the anticipated amount of traffic, the proper balance between performance and cost can be achieved.

A METHOD FOR COMPARISON OF ALTERNATE PAVEMENT DESIGNS

This section presents the possible method originated in this study for comparing various pavement designs for any Indiana State Highway. The comparison permits the selection of the pavement design displaying the greatest amount of performance for the least cost. The method is based upon the performance equations and the three Indiana serviceability equations for rigid, flexible, and overlay pavements, respectively. These equations, which were developed in this study, are given in the results section of this report.

This technique can be used to compare any set of pavement designs under consideration, providing the following data are determined or estimated for the highway section.

1. The anticipated number of equivalent 18-kip single axle loads per day,
2. The lowest acceptable level of terminal serviceability of the pavement,
3. The effective thickness of each design in the set, and
4. The cost associated with each design in the set.

A work sheet is provided in Appendix D for convenience in recording the data and following this method.

Data Needed

The following traffic and cost data should be assembled for each set of designs to be compared. The required information should be recorded on a work sheet.

Applications Per Day

The anticipated number of 18-kip single axle applications per day, W/day, is required. The simplest method of estimating W/day is from the average daily traffic and the truck route class of the highway, with the use of the nomograph given in Figure 4. (ADT is for one direction only.)

The W/day is determined by connecting the value of the initial anticipated average daily traffic, ADTi, and the truck route class (Class I, II, or III) on the scale for the type of pavement (rigid, flexible, or overlay). This line is projected to the right-hand scale of the nomograph, from which W/day is read. Class I truck routes are Interstate Routes and those U.S.-numbered highways which connect major population centers, Class II includes all other primary state highways, and Class III contains all secondary state highways.

If a measure of the anticipated traffic distribution of the highway is available from either loadometer records or truck counts, the weighted equivalence factor may be calculated directly using equivalence factors, or estimated by any of the equations in Table 8. W/day is obtained by multiplying ADTi by this weighted equivalence factor. However, the increase in accuracy attained with this procedure

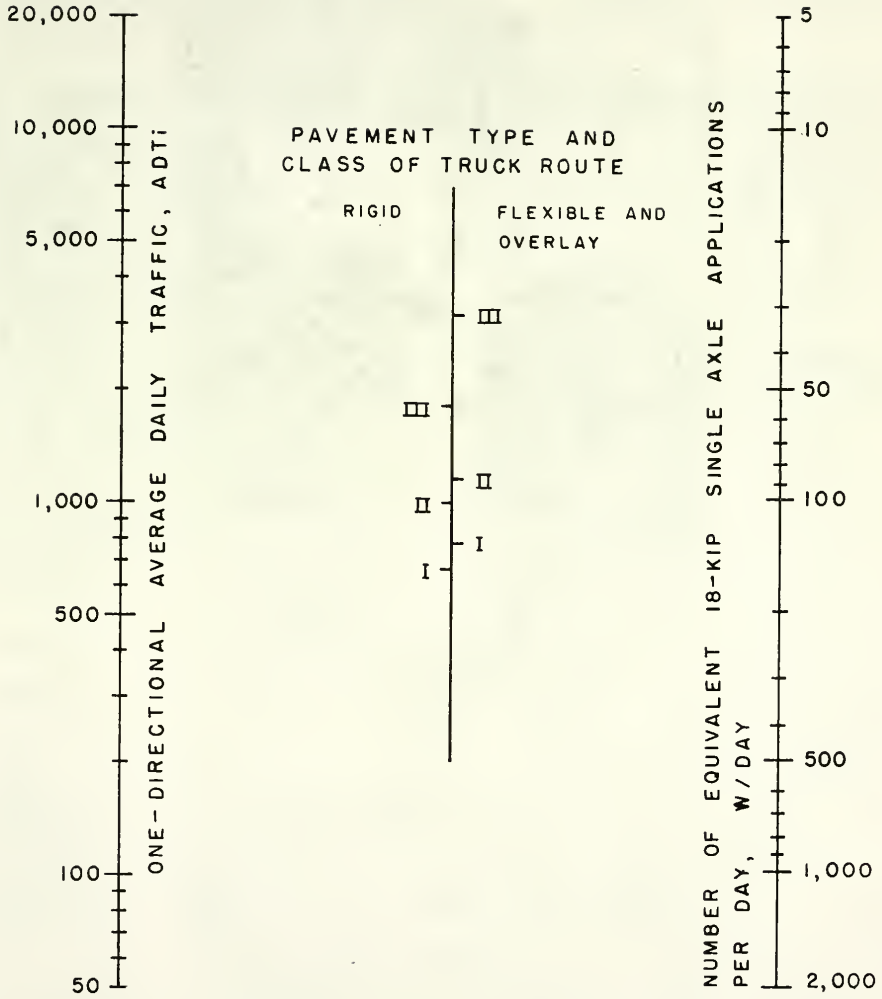

FIGURE 4. NOMOGRAPH FOR DETERMINING THE NUMBER OF 18-KIP SINGLE AXLE APPLICATIONS PER DAY, W/DAY

is slight compared to the uncertainties in estimating the ADT over the life of the pavement. Therefore the use of the nomograph is recommended.

Terminal Serviceability

The present serviceability of a highway section at the time the pavement needs to be resurfaced is termed the terminal serviceability, Pt, of the pavement. If there is no other means of imputing the lowest acceptable level of terminal serviceability for the highway, Table 16 may serve as a guide. In most cases the traffic will begin to slow down because of rough pavement if the present serviceability is less than 2.0. (4)

However, not only the lowest acceptable level of terminal serviceability should be used in choosing the optimum design, but higher levels of terminal serviceability should also be considered, because a large increase in the performance of the pavement section may be possible with only a small increase in cost. In fact, considering that the annual maintenance cost of a pavement increases with the age of the pavement, it is possible that, if the pavement is retired earlier, the annual cost may actually be reduced.

Effective Thickness

Flexible, overlay, and rigid pavements having a wide range of effective thicknesses should be compared, because a large increase in service life can sometimes be achieved with a small increase (1 or 2 in.) in effective thickness.

Table 16. Suggested Terminal Serviceability Levels

Source	Primary Highways	Secondary Highways
AASHO Interim Pavement Design Guides (1, 2)	2.5	2.0
Nakamura (15)		
Acceptable Level	≥ 2.5	≥2.0
Unacceptable Level	≤2.0	≤1.5
BPR Study of Highway Practice in 35 States (17)	2.1	1.9*

* Based on flexible secondary highways only.

On the other hand, a thinner pavement, although replaced sooner, may be less expensive under light traffic conditions because of the lower construction cost to be amortized over the life of the pavement.

For flexible and overlay pavements, a lower cost may be realized by judiciously varying the thicknesses and materials of construction of the component layers. The choice is dependent upon the relative cost and the strength coefficients of the various materials.

The effective thickness of a proposed concrete design equals the thickness of the concrete slab, whenever a base of 3 to 9 in. is used. If the base is eliminated, the effect of the subgrade soil has to be considered in the determination of the effective thickness.

With flexible and overlay designs, the effective thickness or structural number, SN, of the pavement is computed by summing the products of the thickness, Di, and the appropriate strength coefficient, Ai, of each component layer.

$$SN = \sum_{1} (Ai)(Di)$$

The nomograph, Figure 5, can be used to determine the individual products of Ai times Di.

The strength coefficients for the flexible and overlay pavement types which were included in this study are listed in Table 17. Strength coefficients for other materials are given in the section entitled "Effective Thickness of a Pavement" in the review of the literature.

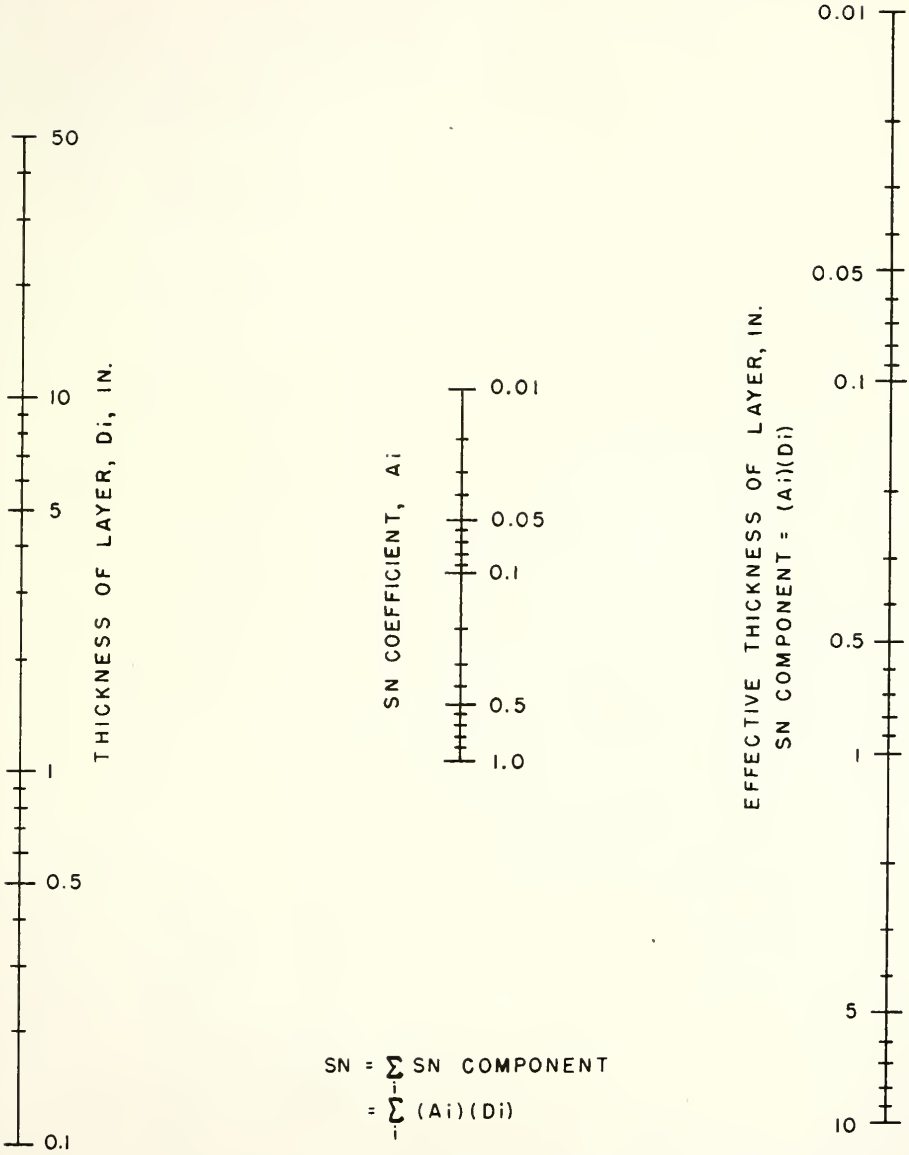

FIGURE 5. NOMOGRAPH FOR DETERMINING THE EFFECTIVE THICKNESS OF FLEXIBLE AND OVERLAY PAVEMENTS

Table 17. Strength Coefficients, Ai, for the Component Layers, i, of Flexible and Overlay Pavements

ISHC No.	Pavement Type	Surface, A1	Base, A2	Subbase, A3
4253	Mixed Bituminous Stabilized Gravel	0.20	0.15	-
6201	Bituminous Concrete, Type B	0.44	0.34	0.11
6202	Mixed Bituminous Concrete on a Non-Rigid Subbase	0.44	0.34	0.11
6221	Rock Asphalt on a Non-Rigid Subbase	0.40	0.34	0.11
6706	Hot Asphalt Concrete on a Rigid Subbase	0.44	0.34	0.40
6726	Rock Asphalt on a Rigid Subbase	0.40	0.34	0.40

These strength coefficients were determined from information in Ref. (1).

The effective thickness of flexible and overlay pavements is modified by the strength of the subgrade as measured by the soil support factor, S. The soil support factor is determined by using the map entitled "Engineering Soil Parent Material Areas of Indiana, JHRP, 1950." a copy of this map is reproduced as Figure 6. The soil support factors are given in Table 18 for the soil units shown on the map.

These soil support factors are independent of the AASHO soil support values. These factors were obtained by a correlation between the mean performance ratings of a panel of soil experts and the serviceability of pavements built on some of these soils.

The effective thickness, SNmod, of the entire pavement system including the subgrade is determined by using Figure 7. A line is drawn between the structural number, SN, as computed above and the soil support factor, S, determined after locating the highway section on the JHRP map. The point "I" of intersection of this constructed line and the Pivot Line on the figure is marked. A second line is then drawn from the point S equals 3.0, through the point "I" to the SN scale. The effective thickness of the entire pavement structure, SNmod, is then read from the intersection of the second line with the right hand scale. If a computer is used, the equation for SNmod given in the "Procedure" can be used instead of Figure 7.

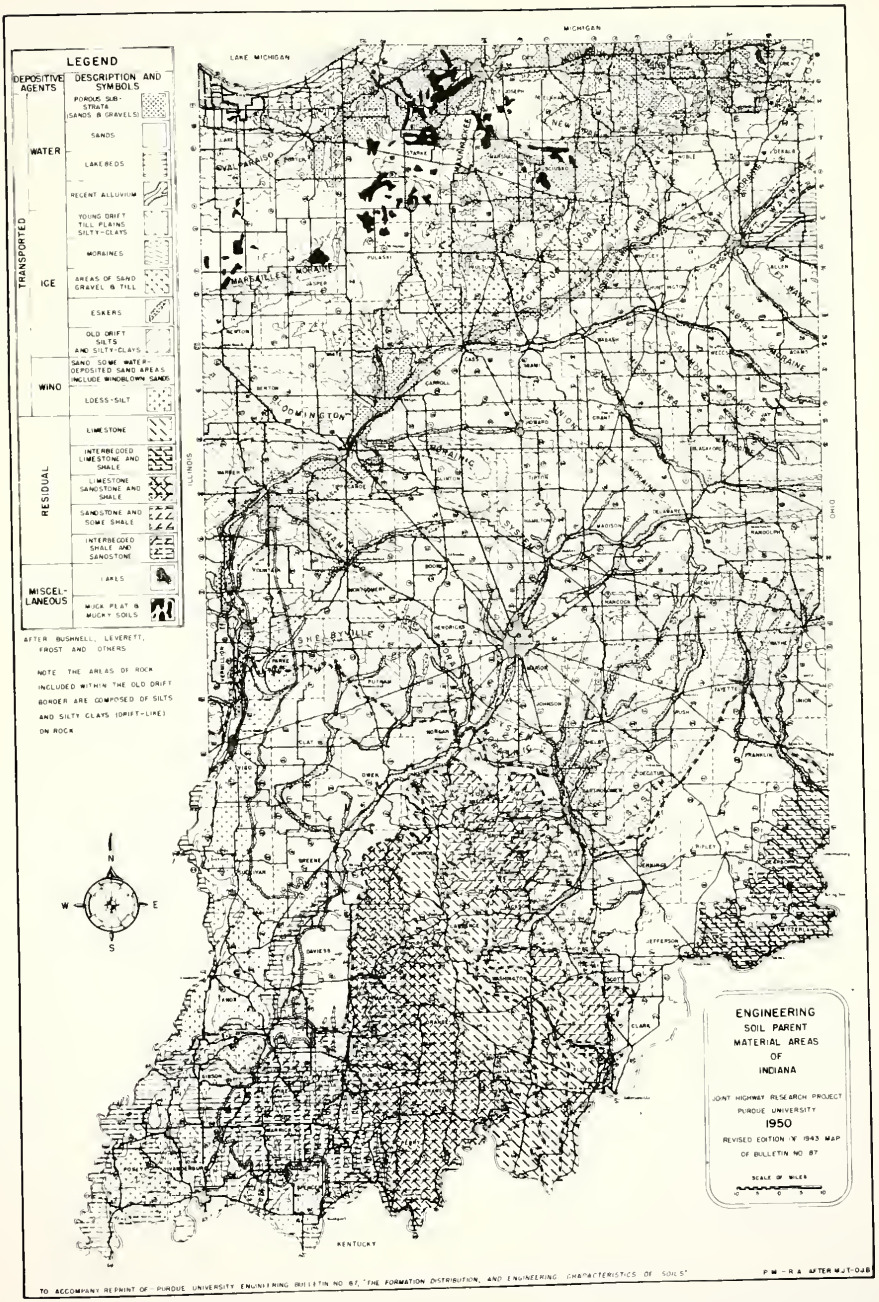

FIGURE 6. MAP FOR DETERMINING MAJOR SOIL UNITS

Table 18. Soil Support Factors for the Major Soil Units of Indiana

Major Soil Unit		Soil Support Factor
Water Transported	(1) Porous Substrata (Sands and Gravels)	6.8
	(2a) Sands (Except Kankakee Sands)	6.2
	(b) Kankakee Sands	5.6
	(3) Lakebeds	4.0
	(4) Recent Alluvium	4.6
Ice Transported	(5) Young Drift Till Plains (Silty-Clays)	4.9
	(6) Moraines	4.9
	(7) Areas of Sand, Gravel, and Till	5.9
	(8) Eskers	6.7
	(9) Old Drift Silts and Silty-Clays	5.0
Wind Transported	(10) Sand: Some Water-Deposited Sand Areas Include Windblown Sands	6.0
	(11) Loess - Silt	5.3
Residual	(12) Limestone	5.1
	(13) Interbedded Limestone and Shale	4.7
	(14) Limestone, Sandstone, and Shale	5.0
	(15) Sandstone and Some Shale	5.4
	(16) Interbedded Shale and Sandstone	4.8
Misc.	(17) Muck, Peat, and Mucky Soils	2.7

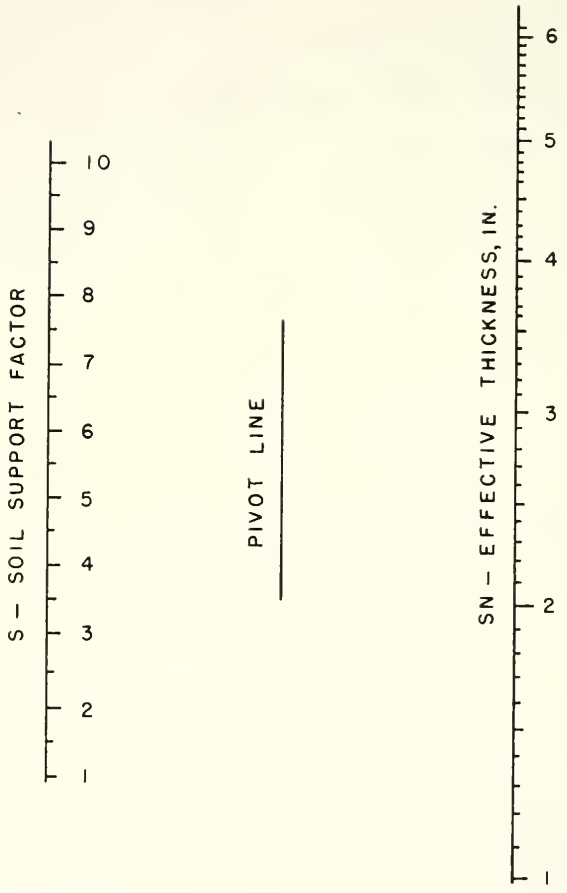

FIGURE 7. SOIL SUPPORT MODIFICATION TO EFFECTIVE THICKNESS FOR FLEXIBLE AND OVERLAY PAVEMENTS SOURCE - REF. (5)

The possibility of stage construction should not be overlooked. The performance of stage designs is computed in separate steps: once for the original pavement, and again for the pavement after each bituminous resurfacing. The effective thickness is computed and used separately for each step. If the original pavement is rigid, the overlay tables are used in subsequent steps. When the original pavement is bituminous pavement, the flexible tables are used for all the steps.

In the performance-cost analysis, the service life of the pavement is considered to be the total design life of all the stages, and the performance is the weighted average performance of all the steps. The weighting is done either by years or by the traffic volumes.

Cost Data

Although any method of computation which results in the total cost per year for each design may be used, a simple method is suggested here. The data needed are the total construction cost of the pavements and the maintenance costs for each year.

Technique

The total number, w, of equivalent 18-kip single axle load applications which will produce the level of terminal serviceability being considered is read from either Table 19, 20, or 21 for each design. The expected life in years for

Table 19. Performance and Total Number of Axle Applications for Rigid Highway Pavements in Indiana

D	Pt	Pa	W	D	Pt	Pa	W
6.5	1.50	3.1	2.37 E6*	8.0	1.50	2.8	9.03 E6
	1.75	3.2	2.22 E6		1.75	3.0	8.23 E6
	2.00	3.2	2.06 E6		2.00	3.1	7.42 E6
	2.25	3.3	1.90 E6		2.25	3.2	6.60 E6
	2.50	3.4	1.73 E6		2.50	3.3	5.76 E6
	2.75	3.5	1.55 E6		2.75	3.4	4.91 E6
	3.00	3.6	1.35 E6		3.00	3.5	4.03 E6
	3.25	3.7	1.14 E6		3.25	3.7	3.13 E6
	3.50	3.8	8.87 E5		3.50	3.8	2.19 E6
	3.75	3.9	5.81 E5		3.75	3.9	1.19 E6
7.0	1.50	3.0	3.80 E6	8.5	1.50	2.8	1.34 E7
	1.75	3.1	3.52 E6		1.75	2.9	1.22 E7
	2.00	3.2	3.23 E6		2.00	3.0	1.09 E7
	2.25	3.3	2.93 E6		2.25	3.2	9.68 E6
	2.50	3.4	2.62 E6		2.50	3.3	8.40 E6
	2.75	3.5	2.29 E6		2.75	3.4	7.10 E6
	3.00	3.6	1.95 E6		3.00	3.5	5.78 E6
	3.25	3.7	1.58 E6		3.25	3.6	4.44 E6
	3.50	3.8	1.17 E6		3.50	3.8	3.06 E6
	3.75	3.9	7.09 E5		3.75	3.9	1.62 E6
7.5	1.50	2.9	5.93 E6	9.0	1.50	2.8	1.96 E7
	1.75	3.0	5.44 E6		1.75	2.9	1.77 E7
	2.00	3.1	4.94 E6		2.00	3.0	1.59 E7
	2.25	3.2	4.43 E6		2.25	3.2	1.40 E7
	2.50	3.3	3.91 E6		2.50	3.3	1.21 E7
	2.75	3.4	3.37 E6		2.75	3.4	1.02 E7
	3.00	3.6	2.80 E6		3.00	3.5	8.23 E6
	3.25	3.7	2.22 E6		3.25	3.6	6.27 E6
	3.50	3.8	1.59 E6		3.50	3.8	4.27 E6
	3.75	3.9	9.02 E5		3.75	3.9	2.21 E6

* 2.37 E6 = 2.37×10^6

Table 19 (cont'd.) (Rigid)

D	Pt	Pa	W	D	Pt	Pa	W
9.5	1.50	2.8	2.80 E7	11.0	1.50	2.8	7.48 E7
	1.75	2.9	2.53 E7		1.75	2.9	6.74 E7
	2.00	3.0	2.26 E7		2.00	3.0	6.00 E7
	2.25	3.1	1.99 E7		2.25	3.1	5.26 E7
	2.50	3.3	1.71 E7		2.50	3.3	4.52 E7
	2.75	3.4	1.44 E7		2.75	3.4	3.77 E7
	3.00	3.5	1.16 E7		3.00	3.5	3.03 E7
	3.25	3.6	8.79 E6		3.25	3.6	2.28 E7
	3.50	3.8	5.94 E6		3.50	3.8	1.53 E7
	3.75	3.9	3.05 E6		3.75	3.9	7.69 E6
10.0	1.50	2.8	3.95 E7	11.5	1.50	2.8	1.01 E8
	1.75	2.9	3.56 E7		1.75	2.9	9.10 E7
	2.00	3.0	3.18 E7		2.00	3.0	8.10 E7
	2.25	3.1	2.79 E7		2.25	3.1	7.09 E7
	2.50	3.3	2.40 E7		2.50	3.3	6.09 E7
	2.75	3.4	2.01 E7		2.75	3.4	5.08 E7
	3.00	3.5	1.62 E7		3.00	3.5	4.07 E7
	3.25	3.6	1.22 E7		3.25	3.6	3.06 E7
	3.50	3.8	8.21 E6		3.50	3.8	2.05 E7
	3.75	3.9	4.18 E6		3.75	3.9	1.03 E7
10.5	1.50	2.8	5.47 E7	12.0	1.50	2.8	1.35 E8
	1.75	2.9	4.98 E7		1.75	2.9	1.21 E8
	2.00	3.0	4.40 E7		2.00	3.0	1.08 E8
	2.25	3.1	3.85 E7		2.25	3.1	9.46 E7
	2.50	3.3	3.31 E7		2.50	3.3	8.11 E7
	2.75	3.4	2.27 E7		2.75	3.4	6.77 E7
	3.00	3.5	2.22 E7		3.00	3.5	5.92 E7
	3.25	3.6	1.68 E7		3.25	3.6	4.07 E7
	3.50	3.8	1.12 E7		3.50	3.8	2.72 E7
	3.75	3.9	5.69 E6		3.75	3.9	1.37 E7

Table 20. Performance and Total Number of Axle Applications for Flexible Highway Pavements in Indiana

SN	Pt	Pa	W	SN	Pt	Pa	W
2.0	1.50	3.1	1.86 E4*	3.5	1.50	2.4	8.30 E5
	1.75	3.2	1.80 E4		1.75	2.6	7.08 E5
	2.00	3.2	1.74 E4		2.00	2.7	5.90 E5
	2.25	3.3	1.66 E4		2.25	2.8	4.76 E5
	2.50	3.3	1.57 E4		2.50	3.0	3.65 E5
	2.75	3.4	1.46 E4		2.75	3.1	2.60 E5
	3.00	3.4	1.32 E4		3.00	3.2	1.61 E5
	3.25	3.5	1.12 E4		3.25	3.4	7.09 E4
2.5	1.50	2.8	7.89 E4	4.0	1.50	2.3	2.22 E6
	1.75	2.9	7.39 E4		1.75	2.4	1.82 E6
	2.00	3.0	6.88 E4		2.00	2.6	1.44 E6
	2.25	3.1	6.27 E4		2.25	2.8	1.09 E6
	2.50	3.2	5.62 E4		2.50	2.9	7.75 E5
	2.75	3.3	4.88 E4		2.75	3.1	5.01 E5
	3.00	3.3	4.00 E4		3.00	3.2	2.27 E5
	3.25	3.4	2.85 E4		3.25	3.4	9.42 E4
3.0	1.50	2.6	2.75 E5	4.5	1.50	2.2	5.43 E6
	1.75	2.7	2.47 E5		1.75	2.4	4.27 E6
	2.00	2.8	2.18 E5		2.00	2.5	3.24 E6
	2.25	2.9	1.87 E5		2.25	2.7	2.33 E6
	2.50	3.1	1.56 E5		2.50	2.9	1.56 E6
	2.75	3.2	1.23 E5		2.75	3.0	9.33 E5
	3.00	3.3	8.85 E4		3.00	3.2	4.51 E5
	3.25	3.4	5.01 E4		3.25	3.3	1.30 E5

* 1.86 E4 = 1.86×10^4

Table 20 (cont'd.) (Flexible)

SN	Pt	Pa	W	SN	Pt	Pa	W
5.0	1.50	2.2	1.23 E7	6.5	1.50	2.1	9.89 E7
	1.75	2.3	9.38 E6		1.75	2.3	7.26 E7
	2.00	2.5	6.89 E6		2.00	2.5	5.08 E7
	2.25	2.7	4.79 E6		2.25	2.6	3.33 E7
	2.50	2.8	3.06 E6		2.50	2.8	1.98 E7
	2.75	3.0	1.72 E6		2.75	3.0	1.02 E7
	3.00	3.2	7.66 E5		3.00	3.2	3.98 E6
	3.25	3.3	1.92 E5		3.25	3.3	7.98 E5
5.5	1.50	2.1	2.59 E7	7.0	1.50	2.1	1.81 E8
	1.75	2.3	1.95 E7		1.75	2.3	1.32 E8
	2.00	2.5	1.40 E7		2.00	2.5	9.16 E7
	2.25	2.7	9.45 E6		2.25	2.6	5.95 E7
	2.50	2.8	5.86 E6		2.50	2.8	3.51 E7
	2.75	3.0	3.15 E6		2.75	3.0	1.78 E7
	3.00	3.2	1.32 E6		3.00	3.2	6.80 E6
	3.25	3.3	2.99 E5		3.25	3.3	1.32 E6
6.0	1.50	2.1	5.19 E7	7.5	1.50	2.1	3.19 E8
	1.75	2.3	3.84 E7		1.75	2.3	2.32 E8
	2.00	2.5	2.72 E7		2.00	2.4	1.60 E8
	2.25	2.6	1.80 E7		2.25	2.6	1.03 E8
	2.50	2.8	1.09 E7		2.50	2.8	6.04 E7
	2.75	3.0	5.72 E6		2.75	3.0	3.03 E7
	3.00	3.2	2.30 E6		3.00	3.2	1.14 E7
	3.25	3.3	4.84 E5		3.25	3.3	2.16 E6

Table 21. Performance and Total Number of Axle Applications for Overlay Highway Pavements in Indiana

SN	Pt	Pa	W	SN	Pt	Pa	W
2.0	1.50	3.5	1.86 E4*	3.5	1.50	2.7	8.30 E5
	1.75	3.6	1.82 E4		1.75	2.8	7.32 E5
	2.00	3.6	1.76 E4		2.00	2.9	6.37 E5
	2.25	3.7	1.71 E4		2.25	3.1	5.44 E5
	2.50	3.7	1.64 E4		2.50	3.2	4.53 E5
	2.75	3.8	1.57 E4		2.75	3.3	3.65 E5
	3.00	3.8	1.49 E4		3.00	3.5	2.81 E5
	3.25	3.9	1.39 E4		3.25	3.6	2.00 E5
	3.50	3.9	1.25 E4		3.50	3.7	1.24 E5
	3.75	4.0	1.06 E4		3.75	3.9	5.44 E4
2.5	1.50	3.2	7.89 E4	4.0	1.50	2.5	2.22 E6
	1.75	3.3	7.50 E4		1.75	2.6	1.89 E6
	2.00	3.3	7.08 E4		2.00	2.8	1.58 E6
	2.25	3.4	6.63 E4		2.25	2.9	1.29 E6
	2.50	3.5	6.15 E4		2.50	3.1	1.02 E6
	2.75	3.6	5.62 E4		2.75	3.3	7.75 E5
	3.00	3.7	5.04 E4		3.00	3.4	5.52 E5
	3.25	3.8	4.38 E4		3.25	3.6	3.57 E5
	3.50	3.8	3.59 E4		3.50	3.7	1.93 E5
	3.75	3.9	2.55 E4		3.75	3.9	6.71 E4
3.0	1.50	2.9	2.75 E5	4.5	1.50	2.4	5.43 E6
	1.75	3.0	2.53 E5		1.75	2.6	4.49 E6
	2.00	3.1	2.29 E5		2.00	2.7	3.64 E6
	2.25	3.2	2.06 E5		2.25	2.9	2.86 E6
	2.50	3.3	1.81 E5		2.50	3.0	2.17 E6
	2.75	3.4	1.56 E5		2.75	3.2	1.56 E6
	3.00	3.6	1.30 E5		3.00	3.4	1.05 E6
	3.25	3.7	1.03 E5		3.25	3.5	6.25 E5
	3.50	3.8	7.37 E4		3.50	3.7	3.02 E5
	3.75	3.9	4.18 E4		3.75	3.8	8.71 E4

* 1.86 E4 = 1.86×10^4

Note: An overlay pavement is a bituminous - resurfaced rigid pavement.

Table 21 (cont'd.) (Overlay)

SN	Pt	Pa	W	SN	Pt	Pa	W
5.0	1.50	2.3	1.23 E7	6.5	1.50	2.3	9.89 E7
	1.75	2.5	9.93 E6		1.75	2.4	7.75 E7
	2.00	2.7	7.84 E6		2.00	2.6	5.90 E7
	2.25	2.8	6.00 E6		2.25	2.8	4.33 E7
	2.50	3.0	4.41 E6		2.50	3.0	3.03 E7
	2.75	3.2	3.06 E6		2.75	3.1	1.98 E7
	3.00	3.3	1.96 E6		3.00	3.3	1.18 E7
	3.25	3.5	1.10 E6		3.25	3.5	6.07 E6
	3.50	3.7	4.90 E5		3.50	3.7	2.37 E6
	3.75	3.8	1.23 E5		3.75	3.8	4.76 E5
5.5	1.50	2.3	2.59 E7	7.0	1.50	2.2	1.81 E8
	1.75	2.5	2.07 E7		1.75	2.4	1.41 E8
	2.00	2.6	1.61 E7		2.00	2.6	1.07 E8
	2.25	2.8	1.21 E7		2.25	2.8	7.78 E7
	2.50	3.0	8.66 E6		2.50	3.0	5.40 E7
	2.75	3.2	5.86 E6		2.75	3.1	3.51 E7
	3.00	3.3	3.63 E6		3.00	3.3	2.07 E7
	3.25	3.5	1.96 E6		3.25	3.5	1.05 E7
	3.50	3.7	8.20 E5		3.50	3.7	4.01 E6
	3.75	3.8	1.85 E5		3.75	3.8	7.78 E5
6.0	1.50	2.3	5.19 E7	7.5	1.50	2.2	3.19 E8
	1.75	2.4	4.07 E7		1.75	2.4	2.48 E8
	2.00	2.6	3.14 E7		2.00	2.6	1.87 E8
	2.25	2.8	2.33 E7		2.25	2.8	1.36 E8
	2.50	3.0	1.65 E7		2.50	2.9	9.36 E7
	2.75	3.1	1.09 E7		2.75	3.1	6.04 E7
	3.00	3.3	6.62 E6		3.00	3.3	3.54 E7
	3.25	3.5	3.47 E6		3.25	3.5	1.77 E7
	3.50	3.7	1.39 E6		3.50	3.7	6.69 E6
	3.75	3.8	2.93 E5		3.75	3.8	1.27 E6

each design is determined from either Figure 8, 9, or 10. These nomographs implicitly convert the initial ADT to an average ADT for the life of the pavement. An annual growth rate for the traffic of 4, 6, or 8 percent is assumed by choosing the appropriate figure. A line is drawn on the chosen nomograph from W to W/day, and then the expected life in years, Y, is read from the middle scale.

The formula that was used in preparing these figures is:

$$ADTa = \frac{ADTi + ADTt}{2.0} = \frac{ADTi + (1.0 + r)^{Y} ADTi}{2.0}$$

where:

ADTa = the average ADT over the service life of the pavement, in one direction,

ADTi = the initial ADT at the time the pavement is opened to traffic after being constructed or being resurfaced, in one direction,

ADTt = the terminal ADT at the end of the design period,

Y = the expected life of the pavement in years, and

r = the annual growth rate of traffic assumed.

If a traffic growth rate other than 4, 6, or 8 percent is probable, then the equation:

$$Y\ (1.0 + (1.0 + r)^{Y}) = \frac{2.0\ W}{365.0\ (W/day)}$$

may be solved for Y by a trial-and-error procedure.

The average annual cost associated with each design is determined from either past records or estimating procedures currently in use. The desired degree of refinement may be attained by including in the analysis, in addition to

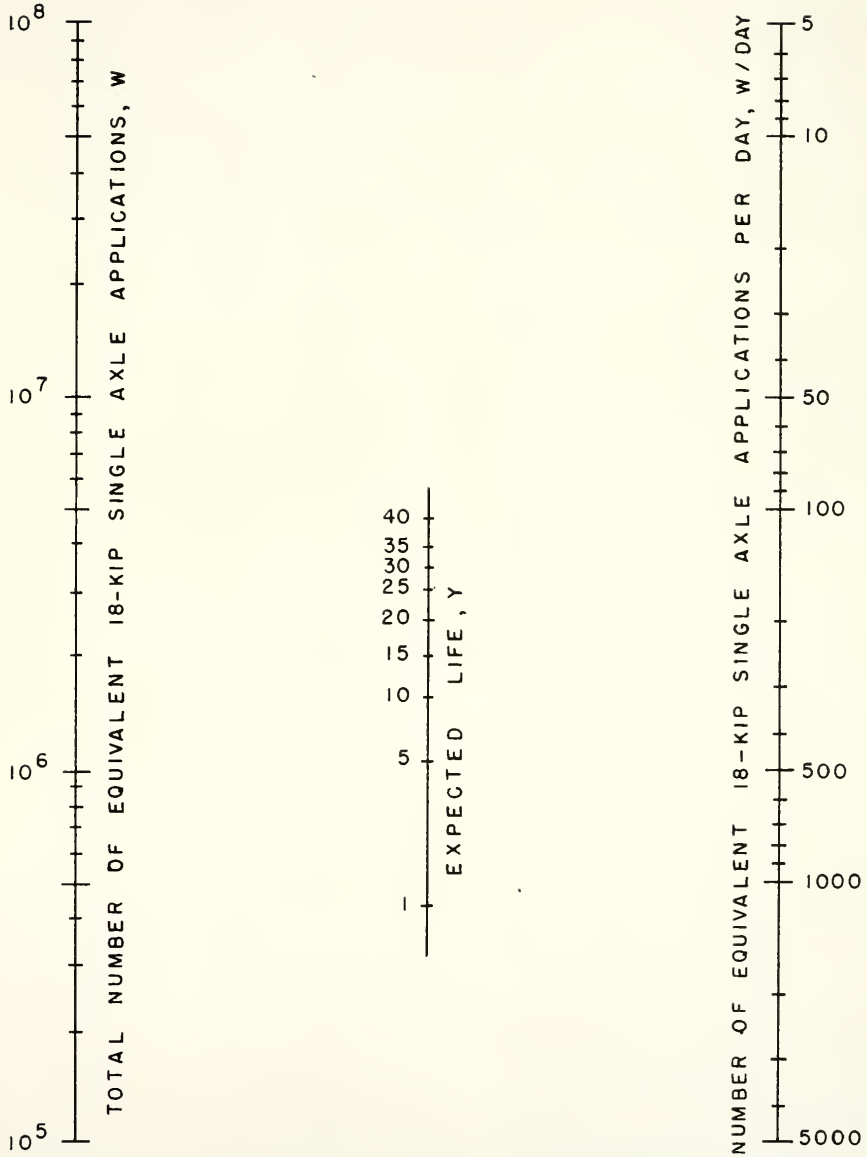

FIGURE 8. EXPECTED LIFE OF A PAVEMENT FOR A TRAFFIC GROWTH RATE OF 4 PERCENT PER YEAR

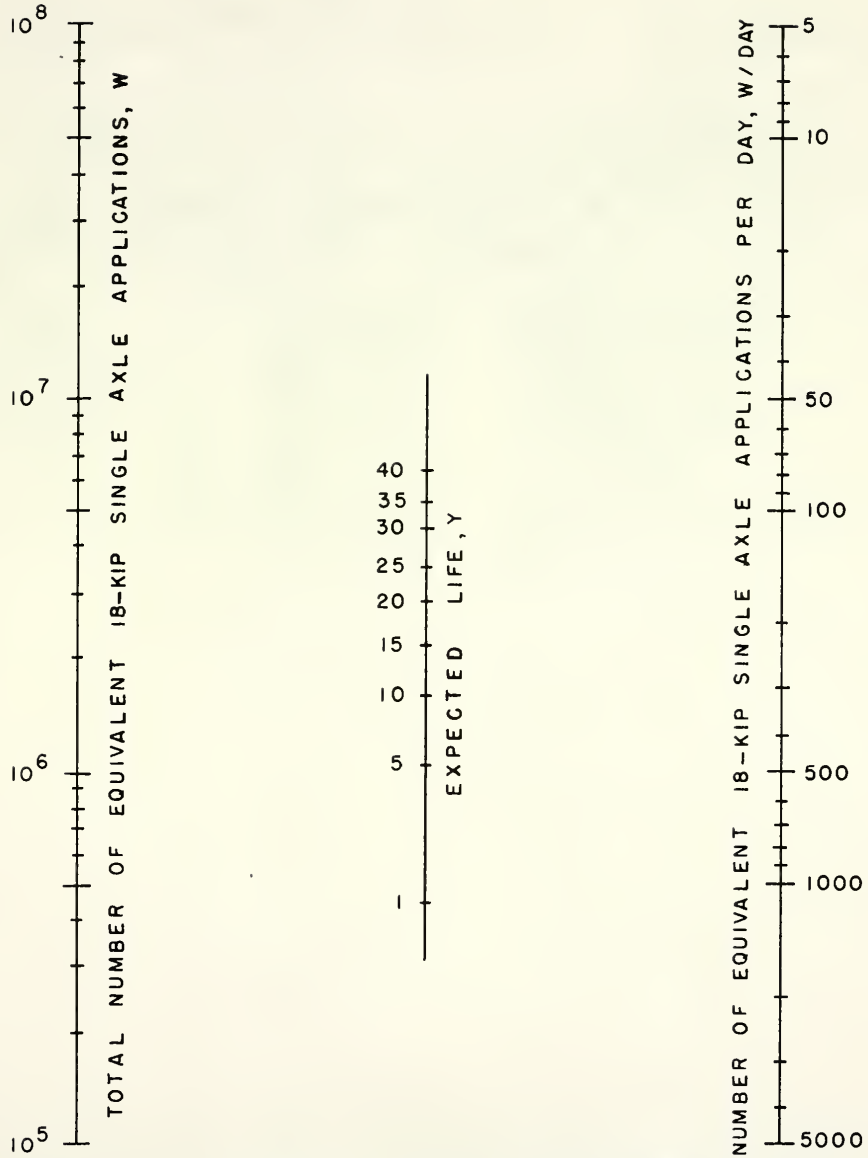

FIGURE 9. EXPECTED LIFE OF A PAVEMENT FOR A TRAFFIC GROWTH RATE OF 6 PERCENT PER YEAR

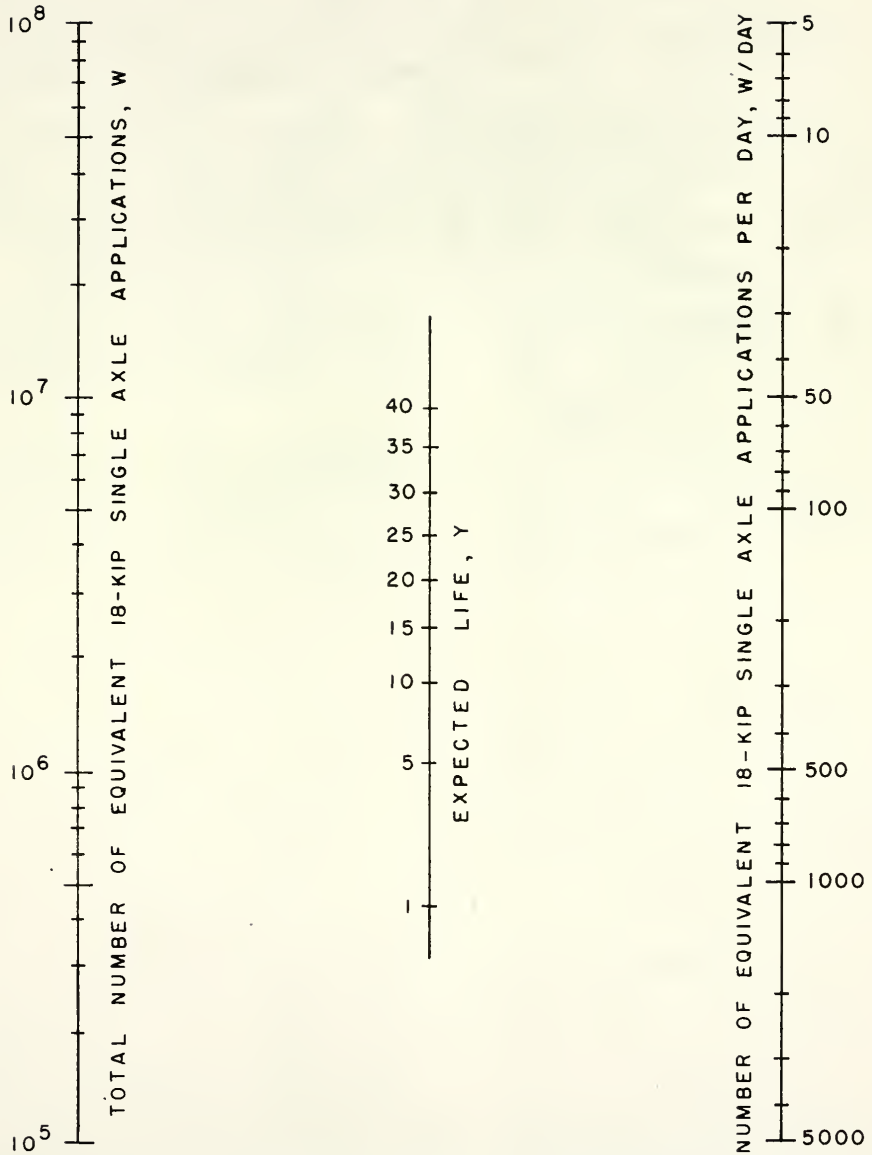

FIGURE 10. EXPECTED LIFE OF A PAVEMENT FOR A TRAFFIC GROWTH RATE OF 8 PERCENT PER YEAR

materials and labor construction costs, maintenance, interest, engineering, and road user costs, depreciation, and salvage. The data comprising the average annual cost are usable in any consistent unit, such as dollars per mile, dollars per square yard, etc., as long as the same unit is used for all costs.

The average annual cost, Cyr, of the pavement is the sum of the average annual highway maintenance cost, M, and the average annual pavement capital cost, Cr:

$$Cyr = Cr + M.$$

The average annual maintenance cost, M, is calculated by adding together the maintenance cost, Mi, for each year, i; and then dividing by the expected life, Y:

$$M = \left(\sum_{i=1}^{Y} Mi\right) / Y.$$

If neither an interest rate nor a salvage value is included in the analysis, the average annual annual capital cost, Cr, for each design is computed by dividing the construction cost, C, by the expected life, Y, i.e.

$$Cr = C/Y .$$

If an interest rate and a salvage value are imputed, one of the annual capital cost formulas which include depreciation of the investment and an interest charge on the investment is used. Three of the preferred formulas of this type are the "straight-line", "sinking fund", and "capital recovery with return interest". The latter is as follows:

$$Cr = (C - Vs)\left[\frac{I\,(1.0 + I)^{Y}}{(1.0 + I)^{Y} - 1.0}\right] + (I)(Vs)$$

where:

Cr = the average annual capital cost of the pavement,

C = the total construction cost of the pavement,

Vs = the salvage value of the pavement at the end of Y years,

I = the applicable interest rate, and

Y = the number of years before a terminal serviceability of Pt is reached.

This method for comparision of designs requires that the economic data be in the form of an average annual cost, because the performance data is in terms of the average serviceability of the pavement.

When the average annual cost is computed for a stage construction design or for a reconstruction design, resurfacing costs are treated as capital costs.

Actually, the distinction between conventional and stage construction is an economic fiction. An existing highway pavement is seldom entirely abandoned or removed. It is generally resurfaced repeatedly and kept in service, at least as a local access road. The difference is that, with stage construction design the economic design life used in the calculaion of the costs includes more than one stage of this recurring process.

The performance, Pa, as a function of the pavement type and effective thickness of each design for each level of terminal serviceability under consideration is found in

either Table 19, 20, or 21. In the case of stage construction the performance is obtained for each stage from the appropriate table. The weighted average performance, Pa, is computed by multiplying the performance, Paj, for each stage, j, by the total number of equivalent 18-kip single axle applications, Wj, passing over that stage; summing the products; and then dividing by the grand total number of equivalent axle applications, W, that have traveled over all the stages. The formula notation is:

$$Pa = \frac{\sum_j W_j \, Pa_j}{\sum_j W_j}$$

Alternatively, the weighted average performance can be approximated by weighting the performance of each stage by the number of years, Yj, that each stage, j, is subjected to traffic rather than by Wj.

The comparision of the designs is made after both Pa and Cyr have been computed for all combinations of pavement design and terminal serviceability level to be included in the analysis. The performance to annual cost ratio, Pa/Cyr, is computed for the design with the lowest average annual cost. This design is designated the "standard" design.

The incremental performance to annual cost ratio, P'/C', is computed for each design, k, from the formula:

$$P'/C' = \frac{Pa_k - Pa_o}{Cyr_k - Cyr_o}$$

where:

P'/C' = the incremental performance-to-average-annual-cost ratio,

Pa_k and Pa_o are the performance of design k, and the performance of the standard, respectively, and

Cyr_k and Cyr_o are the average annual cost of design k, and the average annual cost of the standard.

Whenever the quantity $(Pa_k - Pa_o)$ is less than 0.2, the difference in performance is negligible, and design k can be compared to the standard on the basis of cost alone.

For each design having a significant difference in performance from the standard, the P'/C' is compared to the Pa/Cyr ratio of the standard. By this method, the design chosen is the one having the highest P'/C', if this ratio is greater than the Pa/Cyr of the standard. Otherwise, the standard is chosen. The pavement design selected in this manner should display the greatest average serviceability, or performance, for the least cost, of all the designs considered for the given highway location.

SUMMARY OF RESULTS AND CONCLUSIONS

The following results and conclusions are drawn from this study of highway pavement performance and economics:

1. The Carey and Irick "Pavement Serviceability-Performance Concept" is workable in application.

The AASHO Performance Equations (P-equations) were modified in this study for more precise prediction of the present serviceability of rigid, flexible, and overlay Indiana State highways. The modifications proposed reflect primarily the difference in initial serviceability values between Indiana highway pavements and AASHO Road Test pavements.

2. The rigid, flexible, and overlay serviceability equations developed for Indiana highway pavements are of the form:

$$P_{Ind} = A + B\,(W / \rho 18)^{\beta 18}$$

where:

P_{Ind} = the predicted present serviceability of a pavement,

A = the average initial present serviceability for the pavement type: 4.0 for rigid, 3.5 for flexible, and 4.0 for overlay,

B = (A - 1.5) = 2.5, 2.0, and 2.5 for rigid, flexible, and overlay pavements, respectively,

W = the number of equivalent 18-kip single axle applications, and

ρ_{18} and β_{18} = the values of the AASHO equations for Rho and Beta for an 18-kip single axle and for the effective thickness of the pavement.

3. The Indiana serviceability equations may be applied to the mixed-traffic highway situation by the use of equivalence factors, weighted equivalence factors, or equivalence coefficients developed in this study.

4. The results suggest that, for practical purposes, equivalence factors for various axle loads on a given pavement type are primarily functions of axle load and type (single or tandem) only, and that the influence of the terminal serviceability and the effective thickness of the pavement can be eliminated.

5. A weighted equivalence factor, which is the average equivalence factor of an entire traffic stream, is presented. This quantity can be approximated from the percentage of trucks on a highway.

6. An equivalence coefficient, which is an estimate of the weighted equivalence factor for a highway, was developed in this study. Six equivalence coefficients were determined: 0.22, 0.10, and 0.03 for rigid pavements, and 0.16, 0.07, and 0.01 for flexible and overlay pavements, of Class I, II, and III, respectively. The class of a highway refers to its use or non-use as a route for heavy truck transport. The truck-route class of a highway is determined from the following analysis:

Class I includes all Interstate routes and U.S.-numbered routes connecting major population centers.

Class II consists of all other primary state highways.

Class III contains all secondary state highways.

7. The validity of the AASHO soil support scale is unproved. The correlation of this scale with highway pavement performance and with strength tests throughout the range of the scale needs to be undertaken.

8. The soil parent material area concept offers a means of approximating the relative strength of a highway subgrade. A panel of experts was asked to rate the major Indiana soil types. A correlation was obtained between the mean rating of a soil type and the expected soil support for pavements built on each soil.

9. The suggested design-comparison technique developed in this study is based on a performance-to-cost ratio. The method considers terminal as well as average serviceability, and cost throughout the design life of the pavement.

10. The concept of average serviceability of a pavement was developed during the course of this study. This quantity, especially in conjunction with the terminal level of serviceability of the pavement and the length of the design life, provides a measure of the entire serviceability trend, or performance, of the highway pavement throughout its life. The equation for average serviceability is:

$$Pa = \frac{Pt + (A)(\beta 18)}{\beta 18 + 1.0} ,$$

where:

Pa = the performance or average serviceability of a given section of pavement during its service life,

Pt = the terminal level of serviceability,

A = the value of the appropriate Indiana serviceability equation when W equals zero. A equals 4.0, 3.5, and 4.0 for rigid, flexible, and overlay pavements, respectively, and

β_{18} = the value of the AASHO equation for Beta for an 18-kip single axle and for the effective thickness of the pavement.

RECOMMENDATIONS FOR FURTHER RESEARCH

The "Pavement Serviceability-Performance Concept" and the work done at the AASHO Road Test have added much to the understanding of pavement design. This study has verified the applicability of the AASHO Interim Guides for Design in Indiana and has developed a workable method of design based on a new measure of performance. However, before this approach to design can be considered wholly definitive, several additional steps are needed.

Seasonal weighting factors and regional factors need to be determined for Indiana as well as for all parts of the country. These factors should be based on several years of deflection measurements on typical flexible pavements throughout the state.

The modification for soil support is the weakest link in the AASHO Performance Equations. A procedure must be found that is both reliable and practical for determining the effect of a given subgrade on the performance of a highway pavement. The topic of soil strength variability under a several-mile stretch of pavement and its influence on performance remains to be investigated. An economic-planned-failure approach might prove fruitful in determining which soil strength value should be used in design: the worst, the average, or the best

of those determined from sampling the soil at the site.

All available loadometer data for this state has been collected in the late summer. The question of seasonal variation in vehicle axle weights should be investigated to determine whether weighted equivalence factors vary with the seasons of the year. If the variation is significant, this data should be combined with future studies of seasonal weighting factors.

The level of performance that a road user desires and is willing to pay for should be further investigated. This question can be attacked from several aspects including toll-roads, tax referenda, and public opinion surveys. The changing condition of the pavement as it effects both road user costs and safety should also be examined.

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APPENDIX A

GRAPHS OF e_{18} AND β_{18}

FOR RIGID AND FLEXIBLE PAVEMENTS

APPENDIX A

GRAPHS OF ρ_{18} AND β_{18} FOR RIGID AND FLEXIBLE PAVEMENTS

The following four graphs show Rho and Beta as functions of effective thickness for an 18-kip equivalent axle load. These figures can be used to solve either the AASHO P-equations or the Indiana serviceability and performance equations.

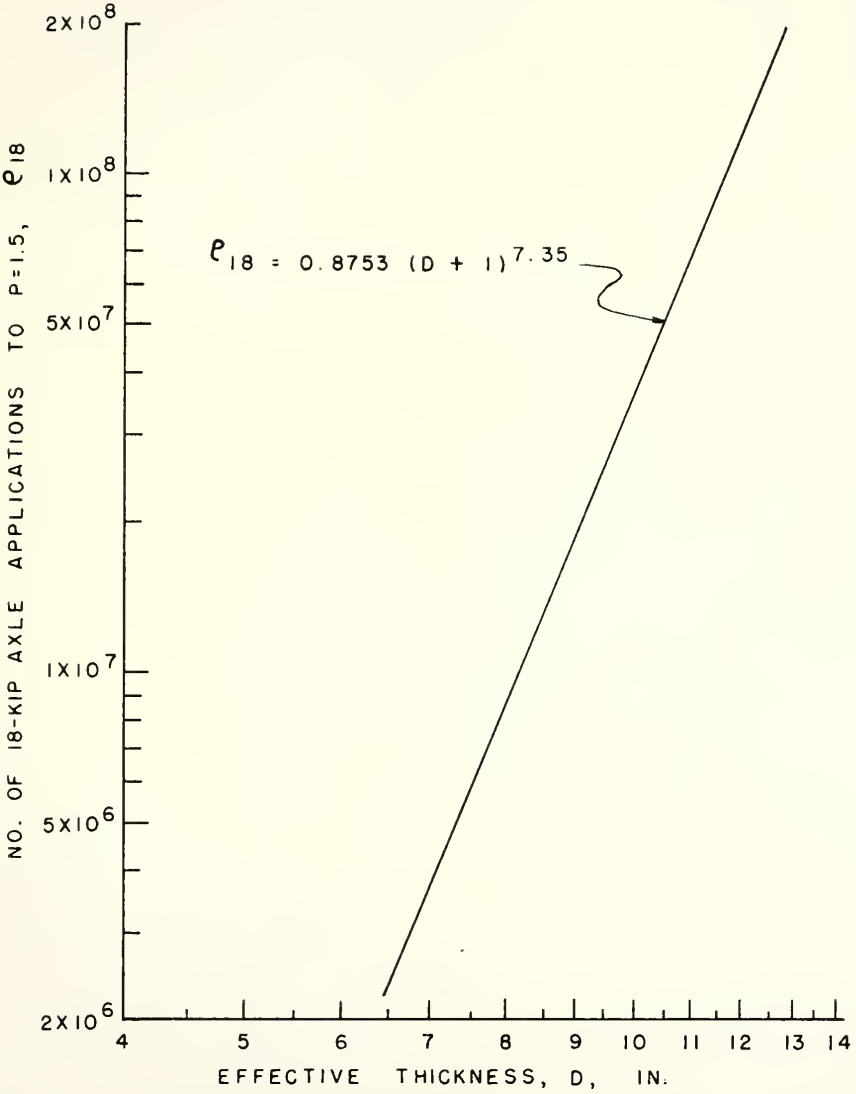


FIGURE 11. RHO_{18} AS A FUNCTION OF EFFECTIVE THICKNESS FOR RIGID PAVEMENTS

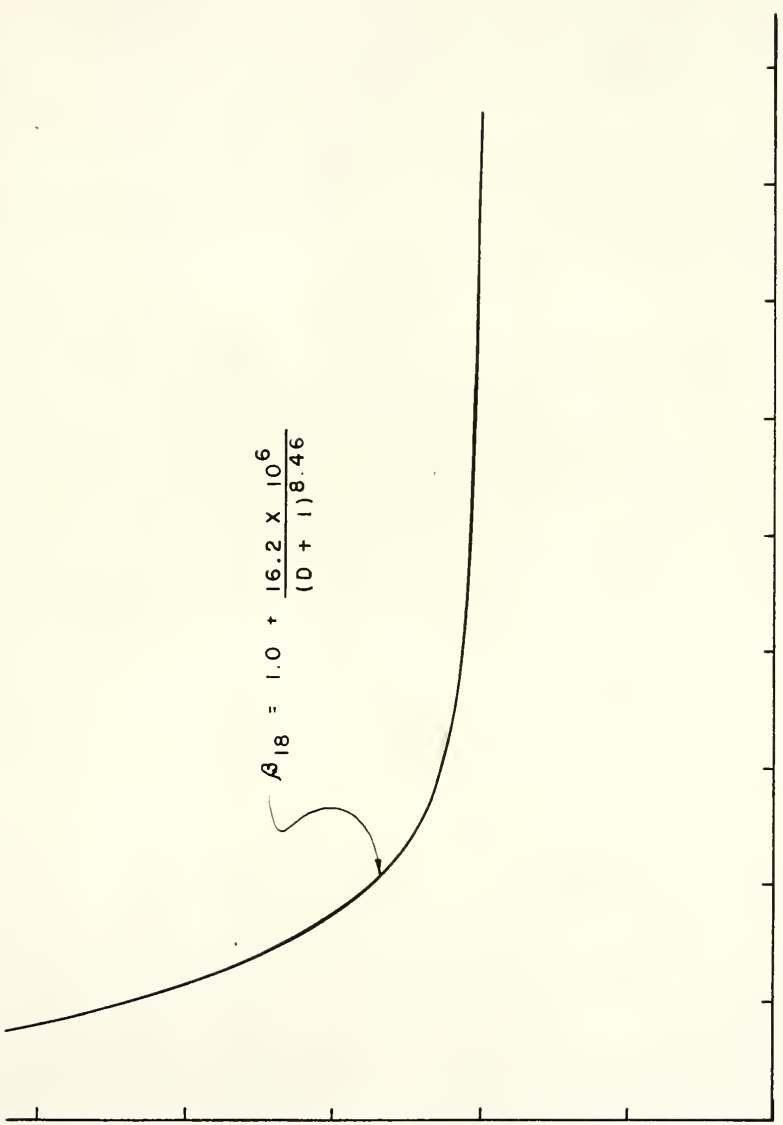


FIGURE 12. BETA$_{18}$ AS A FUNCTION OF EFFECTIVE THICKNESS FOR RIGID PAVEMENTS

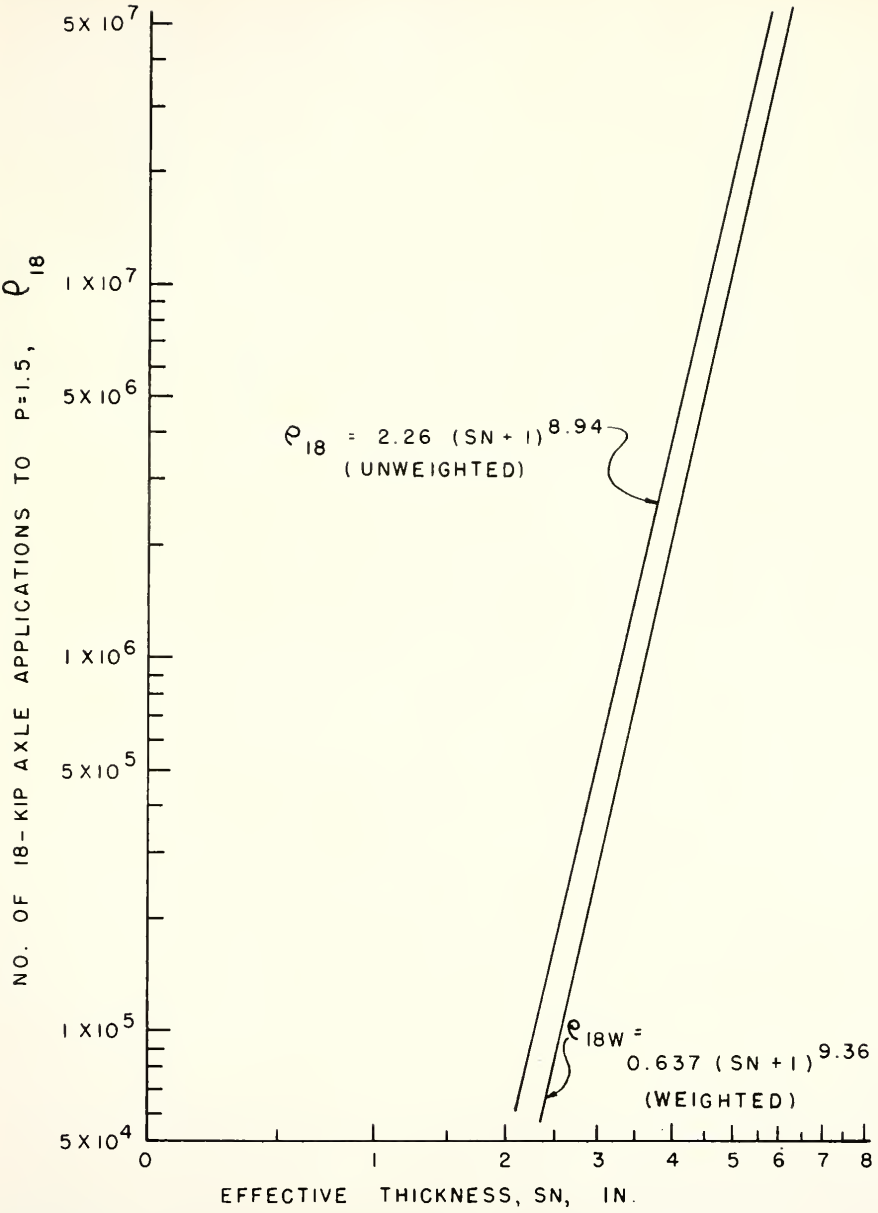


FIGURE 13. RHO_{18} AS A FUNCTION OF EFFECTIVE THICKNESS FOR FLEXIBLE AND OVERLAY PAVEMENTS

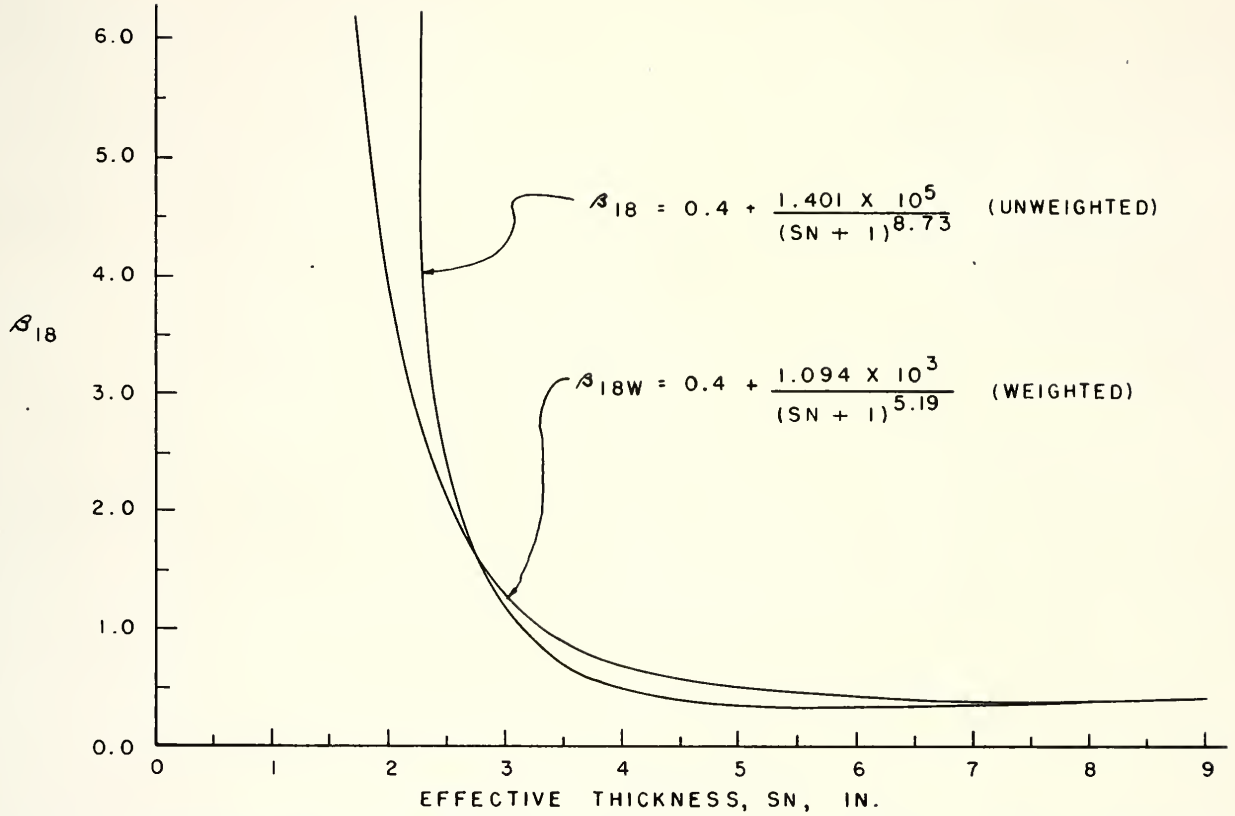


FIGURE 14. BETA$_{18}$ AS A FUNCTION OF EFFECTIVE THICKNESS FOR FLEXIBLE AND OVERLAY PAVEMENTS

APPENDIX E

INSTRUCTIONS TO THE SOIL RATING PANEL

APPENDIX B

INSTRUCTIONS TO THE SOIL RATING PANEL

SUBJECT: Performance of
Flexible Pavements

Dear Sir:

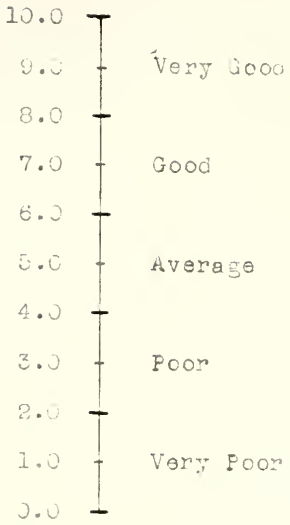
As a part of my thesis I am trying to determine the effect of general soil types and environmental factors on the performance of flexible highway pavements in Indiana. I would like to do this, in part, by means of subjective ratings by a panel of experts.

Enclosed with this letter is a copy of the Joint Highway Research Project map, "Engineering Soil Parent Material Areas of Indiana - 1950." I would appreciate it if you would please help me by rating, on a scale from 0.0 to 10.0, each of the seventeen units (not necessarily contiguous areas) having a common soil type.

The rating of each unit is to be your estimate of the performance of a typical highway built in that unit, based on your knowledge of the soil type, environmental factors, and Indiana State Highway Commission construction practice, such as replacing an organic soil with select material.

It is hoped that conditions do not vary appreciably within a given unit, so that a single rating will be representative of the unit. Even if this is not the case, give a single rating for the unit; however, also indicate the range.

These ratings will be correlated with data which is expressed to the nearest tenth; therefore, please express your rating to the nearest tenth on the following scale:



Expected Pavement Performance

Please record your rating on the attached form, and return it. Thank you very much for your consideration of this request.

APPENDIX C

DERIVATION OF THE

PERFORMANCE EQUATION

APPENDIX C

DERIVATION OF THE PERFORMANCE EQUATION

In general terms the derivation of the equation for estimating performance in terms of serviceability is as follows.

P_a = the mean ordinate of the curve P_{ind} versus W

$$= \frac{\int_{W=Wi}^{W=Wt} \left[P_{ind} \right] \, dW}{Wt - Wi}$$

Substituting:

$$P_a = \frac{\int_{W=0}^{W=Wt} \left[A - B \left(W / \rho_{18} \right)^{\beta_{18}} \right] dW}{Wt - 0}$$

Integrating:

$$P_a = \frac{\left[(A)(W) - \frac{B}{(\beta_{18} + 1)} \left[\frac{W^{(\beta_{18} + 1)}}{\rho_{18}^{\beta_{18}}} \right] \right] \Bigg|_{W=0}^{W=Wt}}{Wt}$$

Evaluating:

$$P_a = \frac{\left[\left\{ (A)(Wt) \right\} - \left\{ \frac{B}{(\beta_{18} + 1)} \left(\frac{Wt}{\rho_{18}} \right)^{\beta_{18}} (Wt) \right\} - 0 \right]}{Wt}$$

Dividing by Wt:

$$Pa = A - \left\{\frac{B}{(\beta_{18} + 1)}\right\}\left\{\frac{(Wt)}{(\rho_{18})}\right\}^{\beta_{18}}$$

Factoring:

$$Pa = \frac{1}{(\beta_{18} + 1)}\left[A\,(\beta_{18} + 1) - B\left\{\frac{Wt}{\rho_{18}}\right\}^{\beta_{18}}\right]$$

Rearranging:

$$Pa = \frac{1}{(\beta_{18} + 1)}\left[A - B\left\{\frac{Wt}{\rho_{18}}\right\}^{\beta_{18}} + A\,(\beta_{18})\right]$$

Substituting Pt:

$$Pa = \frac{1}{(\beta_{18} + 1)}\left[Pt + A\,(\beta_{18})\right]$$

Therefore:

$$Pa = \frac{Pt + A\,(\beta_{18})}{(\beta_{18} + 1)}$$

where:

Pa = the performance or average serviceability of a given section of pavement during its service life,

P_{Ind} = the predicted serviceability as a function of W and pavement design,

W = the cumulative number of equivalent 18-kip single axle load applications,

Wi = 0 = the initial value of W,

Wt = the value of W when P_{Ind} equals Pt,

Pt = the terminal level of serviceability,

A = the value of the appropriate Indiana serviceability equation when W equals Wi, and

β_{18} = the exponent of the appropriate Indiana serviceability equation as a function of the effective thickness of the given pavement.

APPENDIX D

THE RELATIONSHIP BETWEEN EFFECTIVE THICKNESS AND PERFORMANCE

APPENDIX D

THE RELATIONSHIP BETWEEN EFFECTIVE THICKNESS AND PERFORMANCE

It may seem unusual that the performance of a pavement decreases as the effective thickness increases. The necessity of these results is shown in the following manner.

Assume that the effective thickness of design 1 is greater than the effective thickness of design 2. Then, from the formula for $\beta 18$, 0 is less than $\beta 18_1$ is less than $\beta 18_2$. The term (A - Pt) is positive, because the initial serviceability, A, is greater than the terminal serviceability, Pt; so,

$$(A - Pt)(\beta 18_1) < (A - Pt)(\beta 18_2)$$

$$(A)(\beta 18_1) - (Pt)(\beta 18_1) < (A)(\beta 18_2) - (Pt)(\beta 18_2)$$

$$(A)(\beta 18_1) + (Pt)(\beta 18_2) < (A)(\beta 18_2) + (Pt)(\beta 18_1)$$

$$\begin{aligned}(A)(\beta 18_1) + (Pt)(\beta 18_2) \\ + Pt + (A)(\beta 18_1)(\beta 18_2)\end{aligned} < \begin{aligned}(A)(\beta 18_2) + (Pt)(\beta 18_1) \\ + Pt + (A)(\beta 18_1)(\beta 18_2)\end{aligned}$$

$$\begin{aligned}(Pt + (A)(\beta 18_1)) \\ x\ (\beta 18_2 + 1.0)\end{aligned} < \begin{aligned}(Pt + (A)(\beta 18_2)) \ x \\ (\beta 18_1 + 1.0)\end{aligned}$$

$$\frac{Pt + (A)(\beta 18_1)}{\beta 18_1 + 1.0} < \frac{Pt + (A)(\beta 18_2)}{\beta 18_2 + 1.0}$$

and therefore:

$$Pa_1 < Pa_2$$

for the same terminal serviceability, Pt. Although the performance increases with a decrease in effective thickness, in most cases this effect is slight enough not to warrant the additional cost of resurfacing sooner.

APPENDIX E

WORK SHEET

APPENDIX E

WORK SHEET

The following work sheet, Figure 15, can be used to record the data necessary to determine the pavement design having the highest performance for the least cost. This technique is explained in the section entitled "A Method for Comparision of Alternate Pavement Designs."

Figure 15. Work Sheet for Comparing Pavement Designs

Project No. _____

Highway No. _____

I. Data Needed

A. W/day

1. ADTi _____

2. Truck Route Class (Class I, II, or III)_____

3. W/day (Figure 4)

a. For Rigid Designs _____

b. For Flexible and Overlay Designs_____

B. Pt

1. Type of Highway (Primary, Secondary)_____

2. Lowest Acceptable Pt (Table 16) _____

3. Other Pt's to be considered

_____ _____ _____

C. Effective Thickness

1. For Rigid Designs Thickness

Design R1 _____

Design R2 _____

(etc.)

2. For Flexible and Overlay Designs

	Ai (Table 17)	Di	(Ai)(Di) (Fig. 5)
Design F1:			
	A1_____	D1_____	a. (A1)(D1)_____
	A2_____	D2_____	b. (A2)(D2)_____

(I.C.2.) Ai (Table 17) Di (Ai)(Di) (Fig. 5)

A3_____ D3_____ c. (A3)(D3)_____

Design F1 SN = a. + b. + c. = _____

Design F2:

A1_____ D1_____ a. (A1)(D1)_____

A2_____ D2_____ b. (A2)(D2)_____

A3_____ D3_____ c. (A3)(D3)_____

Design F2 SN = a. + b. + c. = _____

(etc.)

3. Soil Support Modification

(For Flexible and Overlay Designs Only)

a. Major Soil Unit (Figure 6) _____

b. Soil Support Factor (Table 18)_____

c. SNmod (Figure 7)

Design F1 _____

Design F2 _____

(etc.)

D. Cost Data

1. Total Construction Cost 2. Maintenance Cost / Yr.

Design R1_____ _____

Design R2_____ _____

Design F1_____ _____

Design F2_____ _____

(etc.)

II. Technique

A. Determination of Cost / Year, Cyr

(Do once for each Design for each Pt in (I.B.))

1. W (Table 19, 20, or 21) _____

2. W/day (I.A.3.a.) or (I.A.3.b.) _____

3. Y (Figure 8, 9, or 10) _____

4. Capital Cost / Year, Cr (I.D.1.) / (3.) or from desired annual capital cost formula _____

5. Maintenance Cost / Year, M (I.D.2.) _____

6. Average Cost / Year, Cyr (4.) + (5.) _____

B. Determination of Performance, Pa

(Do once for each Design)

1. Pt (I.B.2.) and (I.B.3.)	2. Pa (Table 19, 20, or 21)
_____	_____
_____	_____
_____	_____
_____	_____

C. Performance / Cost Ratios

1. Standard Performance and Cost, Pa_o/Cyr_o (To be computed only for Design with lowest Cyr)

a. Pa_o (B.2.) _____

b. Cyr_o (A.6.) _____

c. Pa_o/Cyr_o (a.) / (b.) _____

(II.C.)

2. Incremental Performance / Cost Ratios

a. $Pa_k - Pa_o$ (B.2.) - (C.1.a.)	b. $Cyr_k - Cyr_o$ (A.6.) - (C.1.b.)	c. P'/C' (a.) / (b.)
Design R1:		
_____	_____	_____
Design R2:		
_____	_____	_____
Design F1:		
_____	_____	_____
Design F2:		
_____	_____	_____
(etc.)		

D. Comparison

1. Test for Significance:

Is $(Pa_k - Pa_c) \geqslant 0.2$? (C.2.a.) (Yes or No)

Design R1: _____

Design R2: _____

Design F1: _____

Design F2: _____

(etc.)

2. For each Design for which (D.1.) is "Yes", record P'/C' (C.2.c.).
For the Standard Design, record $Pa/Cyr = Pa_o/Cyr_o$ (C.1.c.).
Disregard any other Design for which (D.1.) is "No".

Design R1: _____

Design R2: _____

(II.D.2) Design F1: _____

Design F2: _____

(etc.)

. Choose the Design with the highest value recorded in (D.2.).

Choice Design No. _____